BIOLOGY OF WATER POLLUTION

A Collection of Selected Papers on Stream Pollution, Waste Water, and Water Treatment

Compiled
by

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PREFACE

Water users are becoming more and more concerned with the abatement of pollution. Accelerated population and industrial growth has brought many persons into intimate contact with problems relating to water degradation that is associated with municipal, industrial, or agricultural wastes, or combinations of these. Thus, the problems of waste disposal and their reasonable solution are today the concern of all. It is apparent that problems attendant to waste disposal and water treatment are increasing. Most people fully appreciate that streams, lakes, and estuarine waters remain static in quantity.

With increased concern for America's water resources, the populace is demanding accelerated programs for the abatement of pollution, and this requires an increased number of personnel trained in and cognizant of environmental science.

Science is common sense based upon the experiences of man. Scientific literature is a record of these experiences. With the growth of the aquatic sciences, the literature has become voluminous, creating an information retrieval problem. In addition, many of the earlier writings were published in limited editions and some in not readily available journals. Today many are not readily available to the scientist who does not have access to a large, long established library.

This book of selected publications on Biology of Water Pollution, Water Treatment, and Sewage and Industrial Waste Treatment contains some of the many excellent and basic pertinent biological papers that have been commonly inaccessible to the contemporary investigator. These papers are often quoted (sometimes incorrectly) and are a portion of the "foundation" upon which modern aquatic ecological scientific thought and decisions are often based in summating water pollution control investigations.

This compiled collection will be of assistance in three phases of water pollution abatement: (1) It will provide a technical service to the aquatic ecologist through the assemblage of informative literature; (2) it will illustrate many of the concepts upon which regulations have been formulated for the protection of aquatic life; (3) it will aid in the training of new environmental scientists to meet today's and tomorrow's personnel needs in the conservation of our Nation's natural resources.

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Cincinnati, Ohio
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Chapter I

GENERAL BACKGROUND OF BIOLOGICAL ASPECTS OF WATER POLLUTION

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THE LAKE AS A MICROCOSM*

Stephen A. Forbes

A lake is to the naturalist a chapter out of the history of a primeval time, for the conditions of life there are primitive, the forms of life are, as a whole, relatively low and ancient, and the system of organic interactions by which they influence and control each other has remained substantially unchanged from a remote geological period.

The animals of such a body of water are, as a whole, remarkably isolated -- closely related among themselves in all their interests, but so far independant of the land about them that if every terrestrial animal were suddenly annihilated it would doubtless be long before the general multitude of the inhabitants of the lake would feel the effects of this event in any important way. It is an islet of older, lower life in the midst of the higher, more recent life of the surrounding region. It forms a little world within itself -- a microcosm within which all the elemental forces are at work and the play of life goes on in full, but on so small a scale as to bring it easily within the mental grasp.

Nowhere can one see more clearly illustrated what may be called the sensibility of such an organic complex, expressed by the fact that whatever affects any species belonging to it, must have its influence of some sort upon the whole assemblage. He will thus be made to see the impossibility of studying completely any form out of relation to the other forms; the necessity for taking a comprehensive survey of the whole as a condition to a satisfactory understanding of any part. If one wishes to become acquainted with the black bass, for example, he will learn but little if he limits himself to that species. He must evidently study also the species upon which it depends for its existence, and the various conditions upon which these depend. He must likewise study the species with which it comes in competition, and the entire system of conditions affecting their prosperity; and by the time he has studied all these sufficiently he will find that he has run through the whole complicated mechanism of the aquatic life of the locality, both animal and vegetable, of which his species forms but a single element.

It is under the influence of these general ideas that I propose to examine briefly to-night the lacustrine life of Illinois, drawing my data from collections and observations made during recent years by myself and my assistants of the State Laboratory of Natural History.

The lakes of Illinois are of two kinds, fluviatile and water-shed. The fluviatile lakes, which are much the more numerous and important, are appendages of the river systems of the state, being situated in the river bottoms and connected with the adjacent streams by periodical overflows. Their fauna is therefore substantially that of the rivers themselves, and the two should, of course, be studied together.

They are probably in all cases either parts of former river channels, which have been cut off and abandoned by the current as the river changed its course, or else are tracts of the high-water beds of streams over which, for one reason or another, the periodical deposit of sediment has gone on less rapidly than over the surrounding area, and which have thus come to form depressions in the surface which retain the waters of overflow longer than the higher lands adjacent. Most of the numerous "horseshoe lakes" belong to the first of these varieties, and the "bluff-lakes," situated along the borders of the bottoms, are many of them examples of the second.

These fluviatile lakes are most important breeding grounds and reservoirs of life, especially as they are protected from the filth and poison of towns and manufactories by which the running waters of the state are yearly more deeply defiled.

The amount and variety of animal life contained in them as well as in the streams related to them is extremely variable, depending chiefly on the frequency, extent, and duration of the spring and summer overflows. This is, in fact, the characteristic and peculiar feature of life in these waters. There is perhaps no better illustration of the methods by which the flexible system of organic life adapts itself, without injury, to widely and rapidly fluctuating conditions. Whenever the waters of the river remain for a long time far beyond their banks, the breeding grounds of fishes and other animals are immensely extended, and their food supplies increased to a corresponding degree. The slow or stagnant backwaters of such an overflow afford the best situations possible for the development of myriads of Entomostraca, which furnish, in turn, abundant food for young fishes of all descriptions. There thus results an outpouring of life -- an extraordinary multiplication of nearly every species, most prompt and rapid, generally speaking, in such as have

* This paper, originally read February 25, 1887, to the Peoria Scientific Association (now extinct), and published in their Bulletin, was reprinted many years ago by the Illinois State Laboratory of Natural History in an edition which has long been out of print. A single copy remaining in the library of the Natural History Survey is used every year by classes in the University of Illinois, and a professor of zoology in a Canadian university borrows a copy regularly from a Peoria library for use in his own classes. In view of this long-continued demand and in the hope that the paper may still be found useful elsewhere, it is again reprinted, with trivial emendations, and with no attempt to supply its deficiencies or to bring it down to date.

the highest reproductive rate, that is to say, in those which produce the largest average number of eggs and young for each adult.

The first to feel this tremendous impulse are the protophytes and Protozoa, upon which most of the Entomostraca and certain minute insect larvae depend for food. This sudden development of their food resources causes, of course, a corresponding increase in the numbers of the latter classes, and, through them, of all sorts of fishes. The first fishes to feel the force of this tidal wave of life are the rapidly-breeding, non-predaceous kinds; and the last, the game fishes, which derive from the others their principal food supplies. Evidently each of these classes must act as a check upon the one preceding it. The development of animalcules is arrested and soon sent back below its highest point by the consequent development of Entomostraca; the latter, again, are met, checked, and reduced in number by the innumerable shoals of fishes with which the water speedily swarms. In this way a general adjustment of numbers to the new conditions would finally be reached spontaneously; but long before any such settled balance can be established, often of course before the full effect of this upward influence has been exhibited, a new cause of disturbance intervenes in the disappearance of the overflow. As the waters retire, the lakes are again defined; the teeming life which they contain is restricted within daily narrower bounds, and a fearful slaughter follows; the lower and more defenseless animals are penned up more and more closely with their predaceous enemies, and these thrive for a time to an extraordinary degree. To trace the further consequences of this oscillation would take me too far. Enough has been said to illustrate the general idea that the life of waters subject to periodical expansions of considerable duration, is peculiarly unstable and fluctuating; that each species swings, pendulum-like but irregularly, between a highest and a lowest point, and that this fluctuation affects the different classes successively, in the order of their dependence upon each other for food.

Where a water-shed is a nearly level plateau with slight irregularities of the surface many of these will probably be imperfectly drained, and the accumulating waters will form either marshes or lakes according to the depth of the depressions. Highland marshes of this character are seen in Ford, Livingston, and adjacent counties,* between the headwaters of the Illinois and Wabash systems and an area of water-shed lakes occurs in Lake and McHenry counties, in northern Illinois.

The latter region is everywhere broken by low, irregular ridges of glacial drift, with no rock but boulders anywhere in sight. The intervening hollows are of every variety, from mere sink-holes, either dry or occupied by ponds, to expanses of several square miles, forming marshes or lakes.

This is, in fact, the southern end of a broad lake belt which borders Lakes Michigan and Superior on the west and south, extending through eastern and northern Wisconsin and northwestern Minnesota, and occupying the plateau which separates the headwaters of the St. Lawrence from those of the Mississippi. These lakes are of glacial origin, some filling beds excavated in the solid rock, and others collecting the surface waters in hollows of the drift. The latter class, to which all the Illinois lakes belong, may lie either parallel to the line of glacial action, occupying valleys between adjacent lateral moraines, or transverse to that line and bounded by terminal moraines. Those of our own state all drain at present into the Illinois through the Des Plaines and Fox; but as the terraces around their borders indicate a former water-level considerably higher than the present one it is likely that some of them once emptied eastward into Lake Michigan. Several of these lakes are clear and beautiful sheets of water, with sandy or gravelly beaches, and shores bold and broken enough to relieve them from monotony. Sportsmen long ago discovered their advantages and club-houses and places of summer resort are numerous on the borders of the most attractive and easily accessible. They offer also an unusually rich field to the naturalist, and their zoology and botany should be better known.

The conditions of aquatic life are here in marked contrast to those afforded by the fluviatile lakes already mentioned. Connected with each other or with adjacent streams only by slender rivulets, varying but little in level with the change of the season and scarcely at all from year to year, they are characterized by an isolation, independence, and uniformity which can be found nowhere else within out limits.

Among these Illinois lakes I did considerable work during October of two successive years, using the sounding line, deep-sea thermometer, towing net, dredge, and trawl in six lakes of northern Illinois, and in Geneva Lake, Wisconsin, just across the line. Upon one of these Illinois lakes I spent a week in October, and an assistant, Prof. H. Garman, now of the University, spent two more, making as thorough a physical and zoological survey of this lake as was possible at that season of the year.

I now propose to give you in this paper a brief general account of the physical characters and the fauna of these lakes, and of the relations of the one to the other; to compare, in a general way, the animal assemblages which they contain with those of Lake Michigan -- where also I did some weeks of active aquatic work in 1881 -- and with those of the fluviatile lakes of central Illinois; to make some similar comparisons with the lakes of Europe; and, finally, to reach the subject which has given the title to this paper -- to study the system of natural interactions by which this mere collocation of plants and animals has been organized as a stable and prosperous community.

First let us endeavor to form the mental picture. To make this more graphic and true to the facts, I will describe to you some typical lakes among those in which we worked; and will then do what I can to furnish you the materials for a picture of the life that swims and creeps and crawls and burrows and climbs through the water, in and on the bottom, and among

* All now drained and brought under cultivation.

the feathery water-plants with which large areas of these lakes are filled.

Fox Lake, in the western border of Lake county, lies in the form of a broad irregular crescent, truncate at the ends, and with the concavity of the crescent to the northwest. The northern end is broadest and communicates with Petite Lake. Two points projecting inward from the southern shore form three broad bays. The western end opens into Nippisink Lake, Crab Island separating the two. Fox River enters the lake from the north, just eastward of this island, and flows directly through the Nippisink. The length of a curved line extending through the central part of this lake, from end to end, is very nearly three miles, and the width of the widest part is about a mile and a quarter. The shores are bold, broken, and wooded, except to the north, where they are marshy and flat. All the northern and eastern part of the lake was visibly shallow -- covered with weeds and feeding water-fowl, and I made no soundings there. The water there was probably nowhere more than two fathoms in depth, and over most of that area was doubtless under one and a half. In the western part, five lines of soundings were run, four of them radiating from Lippincott's Point, and the fifth crossing three of these nearly at right angles. The deepest water was found in the middle of the mouth of the western bay, where a small area of five fathoms occurs. On the line running northeast from the Point, not more than one and three fourths fathoms is found. The bottom at a short distance from the shores was everywhere a soft, deep mud. Four hauls of the dredge were made in the western bay, and the surface net was dragged about a mile.

Long Lake differs from this especially in its isolation, and in its smaller size. It is about a mile and a half in length by a mile in breadth. Its banks are all bold except at the western end, where a marshy valley traversed by a small creek connects it with Fox Lake, at a distance of about two miles. The deepest sounding made was six and a half fathoms, while the average depth of the deepest part of the bed was about five fathoms.

Cedar Lake, upon which we spent a fortnight, is a pretty sheet of water, the head of a chain of six lakes which open finally into the Fox. It is about a mile in greatest diameter in each direction, with a small but charming island bank near the center, covered with bushes and vines -- a favorite home of birds and wild flowers. The shores vary from rolling to bluffy except for a narrow strip of marsh through which the outlet passes, and the bottoms and margins are gravel, sand, and mud in different parts of its area. Much of the lake is shallow and full of water plants; but the southern part reaches a depth of fifty feet a short distance from the eastern bluff.

Deep Lake, the second of this chain, is of similar character, with a greatest depth of fifty-seven feet -- the deepest sounding we made in these smaller lakes of Illinois. In these two lakes several temperatures were taken with a differential thermometer. In Deep Lake, for example, at fifty-seven feet I found the bottom temperature 53-1/2° -- about that of ordinary well-water -- when the air was 63°; and in Cedar Lake, at forty-eight feet, the bottom was 58° when the air was 61°.

Geneva Lake, Wisconsin, is a clear and beautiful body of water about eight miles long by one and a quarter in greatest width. The banks are all high, rolling, and wooded, except at the eastern end, where its outlet rises. Its deepest water is found in its western third, where it reaches a depth of twenty-three fathoms. I made here, early in November, twelve hauls of the dredge and three of the trawl, aggregating about three miles in length, so distributed in distance and depth as to give a good idea of the invertebrate life of the lake at that season.

And now if you will kindly let this suffice for the background or setting of the picture of lacustrine life which I have undertaken to give you, I will next endeavor -- not to paint in the picture; for that I have not the artistic skill. I will confine myself to the humble and safer task of supplying you the pigments, leaving it to your own constructive imaginations to put them on the canvas.

When one sees acres of the shallower water black with water-fowl, and so clogged with weeds that a boat can scarcely be pushed through the mass; when, lifting a handful of the latter, he finds them covered with shells and alive with small crustaceans; and then, dragging a towing net for a few minutes, finds it lined with myriads of diatoms and other microscopic algae, and with multitudes of Entomostraca, he is likely to infer that these waters are everywhere swarming with life, from top to bottom and from shore to shore. If, however, he will haul a dredge for an hour or so in the deepest water he can find, he will invariably discover an area singularly barren of both plant and animal life, yielding scarcely anything but a small bivalve mollusk, a few low worms, and red larvae of gnats. These inhabit a black, deep, and almost impalpable mud or ooze, too soft and unstable to afford foothold to plants even if the lake is shallow enough to admit a sufficient quantity of light to its bottom to support vegetation. It is doubtless to this character of the bottom that the barrenness of the interior parts of these lakes is due; and this again is caused by the selective influence of gravity upon the mud and detritus washed down by rains. The heaviest and coarsest of this material necessarily settles nearest the margin, and only the finest silt reaches the remotest parts of the lakes, which, filling most slowly, remain, of course, the deepest. This ooze consists very largely, also, of a fine organic debris. The superficial part of it contains scarcely any sand, but has a greasy feel and rubs away, almost to nothing, between the fingers. The largest lakes are not therefore, as a rule, by any means the most prolific of life, but this shades inward rapidly from the shore, and becomes at no great distance almost as simple and scanty as that of a desert.

Among the weeds and lily-pads upon the shallows and around the margin -- the Potamogeton, Myriophyllum, Ceratophyllum, Anacharis, and Chara, and the common Nelumbium, -- among these the fishes chiefly swim or lurk, by far the commonest being the barbaric bream[1] or "pumpkin-seed" of northern Illinois, splendid with its green and scarlet and purple

[1] Lepomis gibbosus.

and orange. Little less abundant is the common perch (Perca lutea) in the larger lakes -- in the largest outnumbering the bream itself. The whole sunfish family, to which the latter belongs, is in fact the dominant group in these lakes. Of the one hundred and thirty-two fishes of Illinois only thirty-seven are found in these waters -- about twenty-eight per cent -- while eight out of our seventeen sunfishes (Centrarchinae) have been taken there. Next, perhaps, one searching the pebbly beaches or scanning the weedy tracts will be struck by the small number of minnows or cyprinoids which catch the eye or come out in the net. Of our thirty-three Illinois cyprinoids, only six occur there -- about eighteen per cent -- and only three of these are common. These are in part replaced by shoals of the beautiful little silversides (Labidesthes sicculus), a spiny-finned fish, bright, slender, active, and voracious -- as well supplied with teeth as a perch, and far better equipped for self-defense than the soft-bodied and toothless cyprinoids. Next we note that of our twelve catfishes (Siluridae) only two have been taken in these lakes -- one the common bullhead (Ictalurus nebulosus), which occurs everywhere, and the other an insignificant stone cat, not as long as one's thumb. The suckers, also, are much less abundant in this region than farther south, the buffalo fishes[1] not appearing at all in our collections. Their family is represented by worthless carp[2] by two red-horse[3], by the chub sucker[4] and the common sucker (Catostomus teres), and by one other species. Even the hickory shad[5] -- an ichthyological weed in the Illinois -- we have not found in these lakes at all. The sheepshead[6], so common here, is also conspicuous there by its absence. The yellow bass[7], not rare in this river, we should not expect in these lakes because it is, rather, a southern species; but why the white bass[8], abundant here, in Lake Michigan, and in the Wisconsin lakes, should be wholly absent from the lakes of the Illinois plateau, I am unable to imagine. If it occurs there at all, it must be rare, as I could neither find nor hear of it.

A characteristic, abundant, and attractive little fish is the log perch (Percina caprodes) -- the largest of the darters, slender, active, barred like a zebra, spending much of its time in chase of Entomostraca among the water plants, or prying curiously about among the stones for minute insect larvae. Six darters in all (Ethcostomatinae), out of the eighteen from the state, are on our list from these lakes. The two black bass[9] are the most popular game fishes -- the large-mouthed species being much the most abundant. The pickerels[10], gar[11], and dogfish[12] are there about as here; but the shovel-fish[13] does not occur.

Of the peculiar fish fauna of Lake Michigan -- the burbot[14], white fish[15], trout[16], lake herring or cisco[17], etc., not one species occurs in these smaller lakes, and all attempts to transfer any of them have failed completely. The cisco is a notable fish of Geneva Lake, Wisconsin, but does not reach Illinois except in Lake Michigan. It is useless to attempt to introduce it, because the deeper areas of the interior lakes are too limited to give it sufficient range of cool water in midsummer.

In short, the fishes of these lakes are substantially those of their region -- excluding the Lake Michigan series (for which the lakes are too small and warm) and those peculiar to creeks and rivers. Possibly the relative scarcity of catfishes (Siluridae) is due to the comparative clearness and cleanness of these waters. I see no good reason why minnows should be so few, unless it be the abundance of pike and Chicago sportsmen.

Concerning the molluscan fauna, I will only say that it is poor in bivalves -- as far as our observations go -- and rich in univalves. Our collections have been but partly determined, but they give us three species of Valvata, seven of Planorbis, four Amnicolas, a Melantho, two Physas, six Limnaeas, and an Ancylus among the Gastropoda, and two Unios, an Anodonta, a Sphaerium, and a Pisidium among the Lamellibranchiates. Pisiduim variabile is by far the most abundant mollusk in the oozy bottom in the deeper parts of the lakes; and crawling over the weeds are multitudes of small Amnicolas and Valvatas.

The entomology of these lakes I can merely touch upon, mentioning only the most important and abundant insect larvae. Hiding under stones and driftwood, well aware, no doubt, what enticing morsels they are to a great variety of fishes, we find a number of species of ephemerid larvae whose specific determination we have not yet attempted. Among the weeds are the usual larvae of dragon-flies -- Agrionina and Libellulina, familiar to every one; swimming in open water the predaceous larvae of Corethra; wriggling through the water or buried in the mud the larvae of Chironomus -- the shallow water species white, and those from the the deeper ooze of the central parts of the lakes blood-red and larger. Among Chara on the sandy bottom are a great number and variety of interesting case-worms -- larvae of Phryganeidae -- most of them inhabiting tubes of a slender conical form made of a viscid secretion exuded from the mouth and strengthened and thickened by grains of sand, fine or coarse. One of these cases, nearly naked, but usually thinly covered with diatoms, is especially worthy of note, as it has been reported nowhere in this country except in our collections, and was indeed recently described from Brazil as new. Its generic name is Lagenopsyche, but its species undertermined. These larvae are also eaten by fishes.

Among the worms we have of course a number of species of leeches and of planarians, -- in the mud minute Anguillulidae, like vinegar eels, and a slender Lumbriculus which makes a tubular mud burrow for itself in the deepest water, and also the curious Nais probiscidea, notable for its capacity of multiplication by transverse division.

The crustacean fauna of these lakes is more varied than any other group. About forty species were noted

[1] Ictiobus bubalus. [2] Ictiobus cyprinus. [3] Moxostoma aureolum and M. macrolepidotum. [4] Erimyzon sucetta. [5] Dorosoma cepedianum. [6] Haploidonotus. [7] Roccus interruptus. [8] Roccus chrysops. [9] Micropterus. [10] Esox. [11] Lepidosteus. [12] Amia. [13] Polyodon. [14] Lota. [15] Coregonus clupeiformis. [16] Salvelinus namaycush. [17] Coregonus artedi.

in all. Crawfishes were not especially abundant, and most belonged to a single species, Cambarus virilis. Two amphipods occurred frequently in our collections; one, less common here but very abundant farther south -- Crangonyx gracilis -- and one, Allorchestes dentata, probably the commonest animal in these waters, crawling and swimming everywhere in myriads among the submerged water-plants. An occasional Gammarus fasciatus was also taken in the dredge. A few isopod Crustacea occur, belonging to Mancasellus tenax -- a species not previously found in the state.

I have reserved for the last the Entomostraca -- minute crustaceans of a surprising number and variety, and of a beauty often truly exquisite. They belong wholly, in our waters, to the three orders, Copedoda, Ostracoda, and Cladocera -- the first two predaceous upon still smaller organisms and upon each other, and the last chiefly vegetarian. Twenty-one species of Cladocera have been recognized in our collections, representing sixteen genera. It is an interesting fact that twelve of these species are found also in the fresh waters of Europe. Five cyprids have been detected, two of them common to Europe, and also an abundant Diaptomus, a variety of a European species. Several Cyclops species were collected which have not yet been determined.

These Entomostraca swarm in microscopic myriads among the weeds along the shore, some swimming freely, and others creeping in the mud or climbing over the leaves of plants. Some prefer the open water, in which they throng locally like shoals of fishes, coming to the surface preferably by night, or on dark days, and sinking to the bottom usually by day to avoid the sunshine. These pelagic forms, as they are called, are often exquisitely transparent, and hence almost invisible in their native element -- a charming device of Nature to protect them against their enemies in the open lake, where there is no chance of shelter or escape. Then with an ingenuity in which one may almost detect the flavor of sarcastic humor, Nature has turned upon these favored children and endowed their most deadly enemies with a like transparency, so that wherever the towing net brings to light a host of these crystalline Cladocera, there it discovers also swimming, invisible, among them, a lovely pair of robbers and beasts of prey -- the delicate Leptodora and the Corethra larva.

These slight, transparent, pelagic forms are much more numerous in Lake Michigan than in any of the smaller lakes, and peculiar forms occur there commonly which are rare in the larger lakes of Illinois and entirely wanting in the smallest. The transparent species are also much more abundant in the isolated smaller lakes than in those more directly connected with the rivers.

The vertical range of the animals of Geneva Lake showed clearly that the barrenness of the interiors of these small bodies of water was not due to the greater depth alone. While there were a few species of crustaceans and case-worms which occurred there abundantly near shore but rarely or not at all at depths greater than four fathoms, and may hence be called littoral species, there was, on the whole, little diminution either in quantity or variety of animal life until about fifteen fathoms had been reached. Dredging at four or five fathoms were nearly or quite as fruitful as any made. On the other hand, the barrenness of the bottom at twenty to twenty-three fathoms was very remarkable. The total product of four hauls of the dredge and one of the trawl at that depth, aggregating fully a mile and a half of continuous dragging, would easily go into a two-dram vial, and represents only nine animal species -- not counting dead shells, and fragments which had probably floated in from shallower waters. The greater part of this little collection was composed of specimens of Lumbriculus and larvae of Chironomus. There were a few Corethra larvae, a single Gammarus, three small leeches, and some sixteen mollusks, all but four of which belonged to Pisidium. The others were two Sphaeriums, a Valvata carinata, and a V. sincera. None of the species taken here are peculiar, but all were of the kinds found in the smaller lakes, and all occurred also in shallower water. It is evident that these interior regions of the lakes must be as destitute of fishes as they are of plants and lower animals.

While none of the deep-water animals of the Great Lakes were found in Geneva Lake, other evidences of zoological affinity were detected. The towing net yielded almost precisely the assemblage of species of Entomostraca found in Lake Michigan, including many specimens of Limnocalanus macrurus Sars; and peculiar long, smooth leeches, common in Lake Michigan but not occurring in the small Illinois lakes, were also found in Geneva. Many Valvata tri-carinata lacked the middle carina, as in Long Lake and other isolated lakes of this region.

Comparing the Daphnias of Lake Michigan with those of Geneva Lake, Wis. (nine miles long and twenty-three fathoms in depth), those of Long Lake, Ill. (one and a half miles long and six fathoms deep), and those of other, still smaller, lakes of that region, and the swamps and smaller ponds as well, we shall be struck by the inferior development of the Entomostraca of the larger bodies of water in numbers, in size and robustness, and in reproductive power. Their smaller numbers and size are doubtless due to the relative scarcity of food. The system of aquatic animal life rests essentially upon the vegetable world, although perhaps less strictly than does the terrestrial system, and in a large and deep lake vegetation is much less abundant than in a narrower and shallower one, not only relatively to the amount of water but also to the area of the bottom. From this deficiency of plant life results a deficiency of food for Entomostraca, whether of algae, of Protozoa, or of higher forms, and hence, of course, a smaller number of the Entomostraca themselves, and these with more slender bodies, suitable for more rapid locomotion and wider range.

The difference of reproductive energy, as shown by the much smaller egg-masses borne by the species of the larger lakes, depends upon the vastly greater destruction to which the paludal Crustacea are subjected. Many of the latter occupy waters liable to be exhausted by drought, with a consequent enormous waste of entomostracan life. The opportunity for reproduction is here greatly limited -- in some situations to early spring alone -- and the chances for destruction of the summer eggs in the dry and often dusty soil are so numerous that only the most prolific species can maintain themselves.

Further, the marshes and shallower lakes are the favorite breeding grounds of fishes, which migrate to them in spawning time if possible, and it is from the Entomostraca found here that most young fishes get their earliest food supplies -- a danger from which the deep-water species are measurably free. Not only is a high reproductive rate rendered unnecessary among the latter by their freedom from many dangers to which the shallow-water species are exposed, but in view of the relatively small amount of food available for them, a high rate of multiplication would be a positive injury, and could result only in wholesale starvation.

All these lakes of Illinois and Wisconsin, together with the much larger Lake Mendota at Madison (in which also I have done much work with dredge, trawl, and seine), differ in one notable particular both from Lake Michigan and from the larger lakes of Europe. In the latter the bottoms in the deeper parts yield a peculiar assemblage of animal forms which range but rarely into the littoral region, while in our inland lakes no such deep water fauna occurs, which the exception of the cisco and the large red Chironomus larva. At Grand Traverse Bay, in Lake Michigan, I found at a depth of one hundred fathoms a very odd fish of the sculpin family (Triglopsis thompsoni Gir.) which, until I collected it, had been known only from the stomachs of fishes; and there also was an abundant crustacean, Mysis -- the "opossum shrimp", as it is sometimes called -- the principal food of these deep lake sculpins. Two remarkable amphipod crustaceans also belong in a peculiar way to this deep water. In the European lakes the same Mysis occurs in the deepest part, with several other forms not represented in our collections, two of these being blind crustaceans related to those which in this country occur in caves and wells.

Comparing the other features of our lake fauna with that of Europe, we find a surprising number of Entomostraca identical; but this is a general phenomenon, as many of the more abundant Cladocera and Copepoda of our small wayside pools are either European species, or differ from them so slightly that it is doubtful if they ought to be called distinct.

It would be quite impossible, within reasonable limits, to go into details respecting the organic relations of the animals of these waters, and I will content myself with two or three illustrations. As one example of the varied and far-reaching relations into which the animals of a lake are brought in the general struggle for life, I take the common black bass. In the dietary of this fish I find, at different ages of the individual, fishes of great variety, representing all the important orders of that class; insects in considerable number, especially the various water-bugs and larvae of day-flies; fresh-water shrimps; and a great multitude of Entomostraca of many species and genera. The fish is therefore directly dependent upon all these classes for its existence. Next, looking to the food of the species which the bass has eaten, and upon which it is therefore indirectly dependent, I find that one kind of the fishes taken feeds upon mud, algae, and Entomostraca, and another upon nearly every animal substance in the water, including mollusks and decomposing organic matter. The insects taken by the bass, themselves take other insects and small Crustacea. The crawfishes are nearly omnivorous, and of the other crustaceans some eat Entomostraca and some algae and Protozoa. At only the second step, therefore, we find our bass brought into dependence upon nearly every class of animals in the water.

And now, if we search for its competitors we shall find these also extremely numerous. In the first place, I have found that all our young fishes except the Catostomidae feed at first almost wholly on Entomostraca, so that the little bass finds himself at the very beginning of his life engaged in a scramble for food with all the other little fishes in the lake. In fact, not only young fishes but a multitude of other animals as well, especially insects and the larger Crustacea, feed upon these Entomostraca, so that the competitors of the bass are not confined to members of its own class. Even mollusks, while they do not directly compete with it do so indirectly, for they appropriate myriads of the microscopic forms upon which the Entomostraca largely depend for food. But the enemies of the bass do not all attack it by appropriating its food supplies, for many devour the little fish itself. A great variety of predaceous fishes, turtles, water-snakes, wading and diving birds, and even bugs of gigantic dimensions destroy it on the slightest opportunity. It is in fact hardly too much to say that fishes which reach maturity are relatively as rare as centenarians among human kind.

As an illustration of the remote and unsuspected rivalries which reveal themselves on a careful study of such a situation, we may take the relations of fishes to the bladderwort[1] -- a flowering plant which fills many acres of the water in the shallow lakes of northern Illinois. Upon the leaves of this species are found little bladders -- several hundred to each plant -- which when closely examined are seen to be tiny traps for the capture of Entomostraca and other minute animals. The plant usually has no roots, but lives entirely upon the animal food obtained through these little bladders. Ten of these sacs which I took at random from a mature plant contained no less than ninety-three animals (more than nine to a bladder), belonging to twenty-eight different species. Seventy-six of these were Entomostraca, and eight others were minute insect larvae. When we estimate the myriads of small insects and Crustacea which these plants must appropriate during a year to their own support, and consider the fact that these are of the kinds most useful as food for young fishes of nearly all descriptions, we must conclude that the bladderworts compete with fishes for food, and tend to keep down their number by diminishing the food resources of the young. The plants even have a certain advantage in this competition, since they are not strictly dependent on Entomostraca, as

[1] Utricularia.

the fishes are, but sometimes take root, developing then but very few leaves and bladders. This probably happens under conditions unfavorable to their support by the other method. These simple instances will suffice to illustrate the intimate way in which the living forms of a lake are united.

Perhaps no phenomenon of life in such a situation is more remarkable than the steady balance of organic nature, which holds each species within the limits of a uniform average number, year after year, although each one is always doing its best to break across boundaries on every side. The reproductive rate is usually enormous and the struggle for existence is correspondingly severe. Every animal within these bounds has its enemies, and Nature seems to have taxed her skill and ingenuity to the utmost to furnish these enemies with contrivances for the destruction of their prey in myriads. For every defensive device with which she has armed an animal, she has invented a still more effective apparatus of destruction and bestowed it upon some foe, thus striving with unending pertinacity to outwit herself; and yet life does not perish in the lake, nor even oscillate to any considerable degree, but on the contrary the little community secluded here is as prosperous as if its state were one of profound and perpetual peace. Although every species has to fight its way inch by inch from the egg to maturity, yet no species is exterminated, but each is maintained at a regular average number which we shall find good reason to believe is the greatest for which there is, year after year, a sufficient supply of food.

I will bring this paper to a close, already too long postponed, by endeavoring to show how this beneficent order is maintained in the midst of a conflict seemingly so lawless.

It is a self-evident proposition that a species can not maintain itself continuously, year after year, unless its birth-rate at least equals its death-rate. If it is preyed upon by another species, it must produce regularly an excess of individuals for destruction, or else it must certainly dwindle and disappear. On the other hand, the dependent species evidently must not appropriate, on an average, any more than the surplus and excess of individuals upon which it preys, for if it does so it will continuously diminish its own food supply, and thus indirectly but surely exterminate itself. The interests of both parties will therefore be best served by an adjustment of their respective rates of multiplication such that the species devoured shall furnish an excess of numbers to supply the wants of the devourer, and that the latter shall confine its appropriations to the excess thus furnished. We thus see that there is really a close community of interest between these two seemingly deadly foes.

And next we note that this common interest is promoted by the process of natural selection; for it is the great office of this process to eliminate the unfit. If two species standing to each other in the relation of hunter and prey are or become badly adjusted in respect to their rates of increase, so that the one preyed upon is kept very far below the normal number which might find food, even if they do not presently obliterate each other the pair are placed at a disadvantage in the battle for life, and must suffer accordingly. Just as certainly as the thrifty business man who lives within his income will finally dispossess his shiftless competitor who can never pay his debts, the well-adjusted aquatic animal will in time crowd out its poorly-adjusted competitors for food and for the various goods of life. Consequently we may believe that in the long run and as a general rule those species which have survived, are those which have reached a fairly close adjustment in this particular.[1]

Two ideas are thus seen to be sufficient to explain the order evolved from this seeming chaos; the first that of a general community of interests among all the classes of organic beings here assembled, and the second that of the beneficent power of natural selection which compels such adjustments of the rates of destruction and of multiplication of the various species as shall best promote this common interest.

Have these facts and ideas, derived from a study of our aquatic microcosm, any general application on a higher plane? We have here an example of the triumphant beneficence of the laws of life applied to conditions seemingly the most unfavorable possible for any mutually helpful adjustment. In this lake, where competitions are fierce and continuous beyond any parallel in the worst periods of human history; where they take hold, not on goods of life merely, but always upon life itself; where mercy and charity and sympathy and magnanimity and all the virtues are utterly unknown; where robbery and murder and the deadly tyranny of strength over weakness are the unvarying rule; where what we call wrong-doing is always triumphant, and what we call goodness would be immediately fatal to its possessor, -- even here, out of these hard conditions, an order has been evolved which is the best conceivable without a total change in the conditions themselves; an equilibrium has been reached and is steadily maintained that actually accomplishes for all the parties involved the greatest good which the circumstances will at all permit. In a system where life is the universal good, but the destruction of life the well-nigh universal occupation, an order has spontaneously arisen which constantly tends to maintain life at the highest limit -- a limit far higher, in fact, with respect to both quality and quantity, than would be possible in the absence of this destructive conflict. Is there not, in this reflection, solid ground for a belief in the final beneficence of the laws of organic nature? If the system of life is such that a harmonious balance of conflicting interests has been reached where every element is either hostile or indifferent to every other, may we not trust much to the outcome where, as in human affairs, the spontaneous adjustments of nature are aided by intelligent effort, by sympathy, and by self-sacrifice?

[1] For a fuller statement of this argument, see Bul. Ill. State Lab. Nat. Hist. Vol. I, No. 3, pages 5 to 10.

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SEWAGE, ALGAE AND FISH*

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Much has been written concerning the effects of stream pollutants on fish life. It is the general belief that fish cannot live in a stream polluted by domestic sewage or industrial wastes. The conservationists would like to have all waste materials prevented from entering out streams, thereby returning them, at least partially, to their virgin state. This, of course, would be ideal, but our population has increased to more than one hundred million people, conditions have changed and the clock cannot be turned backwards. Few people, however, seem to realize that domestic sewage, after proper treatment, increases the stream's biological productivity as represented by the plankton and fish population. It is the purpose of this paper to show that treated domestic sewage acts as a fertilizer for a stream in much the same manner as barnyard manure does for field plants.

While making a biological survey of the Ohio River Watershed the author was able to collect a large amount of data on the relation of domestic sewage to aquatic life. The present paper is based upon the data presented in detail in a supplement of a forthcoming report of the Ohio River Pollution Survey (1).

RELATION OF SEWAGE TO ALGAE

The entrance of untreated domestic sewage produces a well defined series of physical, chemical and biological changes in a flowing stream (2). In heavily polluted streams, the region immediately below the source of pollution is characterized by a high bacterial population. The water frequently has a cloudy appearance, high biochemical oxygen demand and a strong disagreeable odor, all indicating general depletion of dissolved oxygen. Masses of gaseous sludge, rising from the bottom of the more sluggish streams, are often noticed floating near the surface of the water. The plankton population in this region is composed largely of bacteria-eating ciliated protozoa, such as Paramecium and Colpidium. Large numbers of stalked ciliates (Vorticella and Carchesium) are frequently found attached to bottom objects. Colorless flagellates may be abundant, with an occasional chlorophyll-bearing species. The total volume of plankton is usually less than 2000 parts per million, but may reach several times that figure if conditions are optimum for the development of large numbers of protozoa. Long streamers of sewage fungus are frequently attached to submerged objects. The fishes that normally penetrate this region are carp and buffalo and they are found near the sewer outlet, feeding upon the raw sewage, where the bacterial action has not yet depleted the dissolved oxygen. These fish survive the prevailing low oxygen concentration by coming to the surface to "gulp" air.

Farther down stream, after sufficient time has elapsed for the masses of bacteria to decompose the sewage, the water tends to become clear and the dissolved oxygen level is sufficiently high to support forage and rough fish. The plankton population is slightly higher than upstream but is still composed largely of ciliated protozoa and colorless flagellates. Chlorophyll-bearing species are beginning to make their appearance in noticeable numbers. Blue-green and filamentous green algae are commonly found along the margins and bottom of the stream. Accumulated oxygen may bring large masses of the bottom algae to the surface of the water and give to the stream an unsightly appearance. (These floating islands of algae should not be confused with the gaseous sludge masses previously mentioned.) The combined photosynthetic action of all the green plants is an important factor in raising the oxygen level, especially on bright sunny days.

The adjacent region farther downstream clearly shows the beneficial effect of the decomposed sewage which entered upstream. The bacterial action in the upper reaches of the stream has oxidized the complex organic compounds present in the sewage to nitrates and phosphates. The availability of these end products as plant foods results in the development of large numbers of chlorophyll-bearing algae, which furnish food for the zooplankton and this food supply results in an increase in the population of mixed fishes (Fig. 1). The photosynthetic action of the green algae in this region increases the dissolved oxygen, often to supersaturation during the day, which, however, decreases at night but seldom to the asphyxial level for fishes.

Still farther downstream the plankton population drops sharply, probably owing largely to the utilization of the available food materials by the heavy growth of plankton in the upstream region. There is a tendency for a reduction in the forage and rough fishes, but the game fishes tend to increase.

The above statements give a brief description of the conditions present in a small stream that receives untreated domestic sewage. However, if the waste

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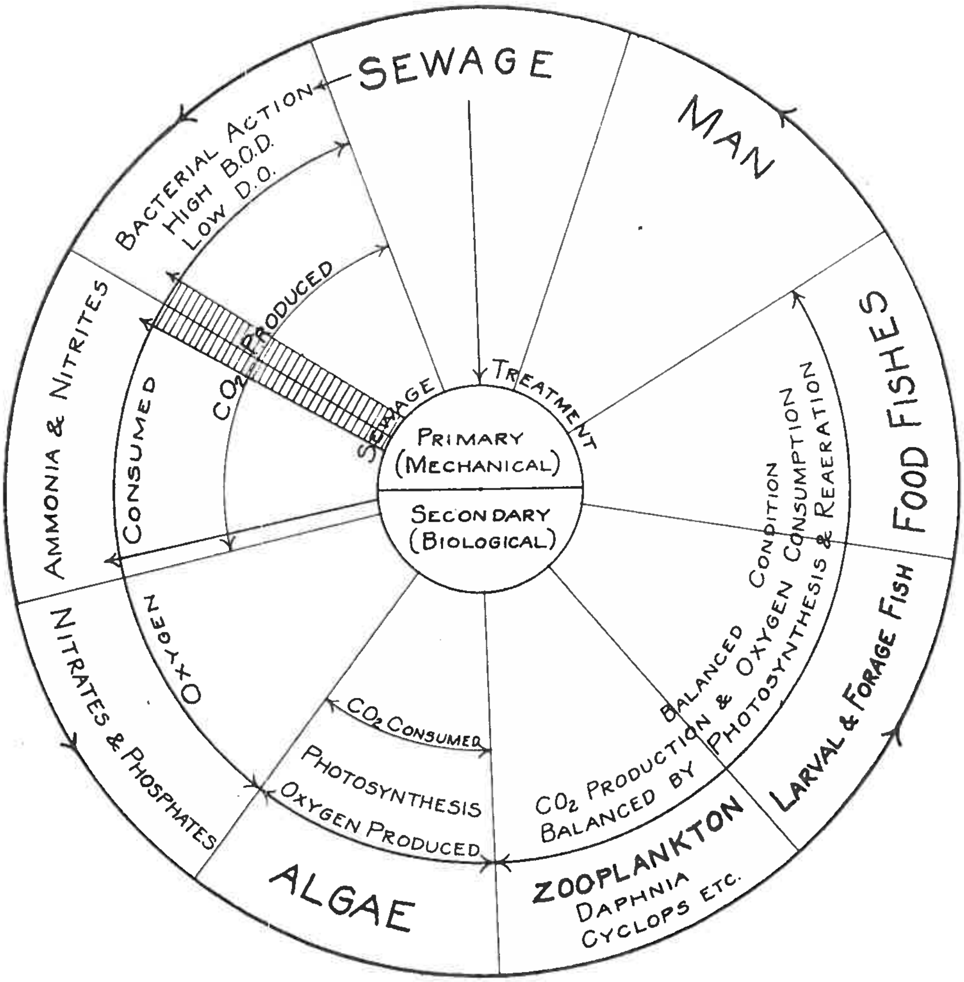

FOOD CYCLE

Figure 1 - Food Cycle in a Polluted Stream. Sewage or other putrescible organic matter after entrance into a flowing stream is changed by bacterial action into ammonia and nitrites and finally into nitrates and phosphates. These latter compounds are assimilated by the algae and result in an increase in growth of these plants. The algae are consumed as food by the larger plankton, zooplankton, which in turn are eaten by fishes. Cross hatched area shows the condition of the effluent as it leaves the treatment plant. The effluent from a primary plant contains some ammonia and nitrites, but is still subject to bacterial action after disposition into the receiving stream. The degradation zone, of high bacterial action, high B.O.D. and low D.O., in the stream can be eliminated by passing the sewage through a complete or secondary treatment plant. Complete treatment converts much of the organic matter into nitrates and phosphates which become immediately available for plant growth resulting in an increased fish population.

receives complete or secondary treatment, so that the bacterial action oxidizes the sewage to available plant foods before the effluent enters the stream, the early obnoxious stage will not occur and the stream will be benefited by the fertilizing effect of the sewage for many miles of its length. Beneficial effects of primary treatment are shown by the reduction in sludge deposits and a shortening of the zone of degradation.

RELATION OF SEWAGE TO FISH LIFE

The effect of sewage on fish life varies with the season and also with the time of day. In summer the fish are active, their metabolic rate is high and more oxygen is required for their respiration than during the winter, when their activity is greatly reduced. On the other hand, during the warm summer periods the bacterial decomposition in a heavily polluted region of a stream is at its maximum, resulting in an increased biological oxygen demand and a lower dissolved oxygen concentration. The solubility of oxygen, moreover, is less in warm water than in cold water, so that less oxygen is absorbed from the atmosphere and held in solution. The increased oxygen requirement of the fish and the reduced oxygen concentration of the water renders hot weather particularly unfavorable for fish life in a polluted stream. Fish, therefore, usually die of suffocation during warm periods in regions grossly polluted by putrescible organic matter. It must not be assumed that summer is the only time that fish suffer from low oxygen concentration, because thousands of fish may die under ice by suffocation owing to the depletion of oxygen by decaying organic matter. This condition may last for only a day or two but that is sufficient time to destroy the fish population in a stream.

The toxicity of the hydrogen sulfide and other compounds produced by anaerobic bacterial action in the bottom sludge deposits may be an important factor in the death of fishes in streams receiving untreated sewage. Ellis (3) reports that 10 p.p.m. of H_2S in hard water killed goldfish in 96 hours or less. Local freshets resulting from heavy rains during low water periods tend to mix the sludge with the supernatant water and to carry the putrid mass downstream. The resulting reduction in the dissolved oxygen and the end products of anaerobic bacterial action destroy the fish for miles below.

It is also well known that heavy organic pollution causes an increase in disease, parasitism and abnormalities among fishes.

The deposition of sludge on the bottom of streams renders that portion of the stream unfit for nesting sites and will smother any eggs that may have been laid prior to the entrance of the waste. Polluted regions may act as barriers to the upstream migration of fish for the purpose of spawning.

RELATION OF ALGAE TO FISH LIFE

Algae serve directly or indirectly as food for all fishes. The green algae are the medium by which the complex organic compounds in sewage, following bacterial decomposition, are transferred to fish. The organic compounds, as previously stated, are converted by bacterial action into available plant foods. These materials are absorbed from the water by the aquatic plants and by the process of photosynthesis, and other cellular activities are converted into the living plant cell. The organic materials comprising the green algae are transferred to the fish through the medium of the zooplankton which are found associated with the algae. Small fish feed directly upon the algae and zooplankton and the adults of many species, such as the shad, live almost entirely upon the microscopic life in the water. The larger zooplankton such as Daphnia, Cyclops, etc., are important articles of diet for larval and small species of fish; in turn, these are eaten by larger fishes which may become the food of man (Fig. 1).

As stated in the first section of this paper, domestic sewage, after it has been decomposed by bacterial action, either in the stream or previously by artificial secondary treatment, increases the growth of aquatic plants by virtue of the fertilizing value of the end products. These plants furnish food for the zooplankton which in turn furnishes food for fish and thus the fish population is increased in regions where stream fertilization by sewage occurs.

Another important factor in the relation of algae to fish life is the reoxygenation of the stream by the photosynthesis of algae. The combined photosynthetic action of all the algae may increase the dissolved oxygen to supersaturation during sunny days. Purdy (4) has shown that Oocystis increases appreciably the amount of oxygen in a closed sample of water. The fact must not be overlooked, however, that the plants themselves, in addition to all forms of aquatic life, consume oxygen during the process of respiration, so the rapid rise of oxygen during the day may be followed by a disastrous fall in the early morning hours if the stream is heavily polluted by decaying organic matter.

Photosynthesis also removes from the water carbon dioxide which is produced as a waste product by the living cell and the decomposition of organic matter. Wells (5) has shown that fishes are very sensitive to small changes in the carbon dioxide content of the water and tend to avoid detrimental concentrations of this gas by moving away to more favorable locations when possible, and that fresh water species of fish tend to select regions where the CO_2 concentration lies between 1 and 6 cc. per liter.

Turbidity may occur in hard-water ponds by the removal of the CO_2 by plants with the subsequent precipitation of the carbonates that are held in solution by the carbonic acid in the water. The removal of CO_2 tends to keep the water from becoming acid, but fish will tolerate without apparent harm a pH as low as 4.5 (6).

SUMMARY

Data obtained from a pollution survey of the Ohio River Basin clearly show that the decomposition products of domestic sewage and other putrescible organic matter increase the growth of plankton, which growth is reflected in an increase in the fish population.

Untreated or raw sewage, when in sufficient concentration, produces a toxic area below the sewer outlet. The region extends downstream for a variable distance, until the sewage is decomposed by bacteria. From this point, the stream is benefited by the fertilizing action of the decomposition products.

When the sewage has received proper secondary treatment, the toxic or degradation zone does not exist and the entire stream will be benefited biologically by the available plant foods introduced.

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BIOLOGICAL ASPECTS OF STREAM POLLUTION*

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The entry of pollutants into a flowing stream sets off a progressive series of physical, chemical and biological events in the downstream waters. Their nature is governed by the character and quantity of the polluting substance. Domestic or industrial effluents may adversely affect natural stream life by direct toxic action or indirectly through quantitative alterations in the character of the water or the stream bed. These facts imply that the presence of polluting substances produces physical, chemical and biological changes that may be recognized as dependable criteria of stream conditions.

The value of physical and chemical data is recognized generally by those concerned with stream pollution and its control. Methods used in gathering these data are fairly well standardized and practiced. Biological procedures have not, as yet, attained an equal degree of refinement. In some ways this is surprising, for the complex interactions resulting from stream pollution are predominantly biological. The determinations of biochemical oxygen demand and dissolved oxygen are essentially for the purpose of finding out how much bacterial food is available and how the bacteria like their diet. Other applications of these data are well known.

The biological phase of stream sanitation is still an infant science, with many of its procedures, refinements and applications still to be worked out. For this reason the following discussion is of a general nature and refers primarily to stream pollution resulting from the introduction of raw or partly treated sewage. Industrial or toxic types of wastes are not considered. Personal field observations and the publications of others have been drawn upon freely for interpretation.

Biological aspects of stream pollution will be considered in a general way from two separate but related points of view: (1) how pollutants change the character of the stream as a habitat for organisms, and (2) the action of organisms upon the pollutant and their related distribution.

The fundamentals of stream biology may best be illustrated by reference to a fictional stream whose hypothetical character may be molded with a free hand. This stream has a semi-solid bottom, medium gradient, average width of about 75 feet, and depth of 6 feet. It flows through alternating wooded and cultivated areas. It is blessed, for our purpose, by having a single source of man-made pollution -- the community of Windmill. Sewage is discharged directly to the stream.

The stream water reaching this community is not pure, for the word, as commonly used, is only relative. Drainage from the land already has added humus extracts, organic particulate matter and inorganic salts leached from the soil. Drainage from cultivated land is rich in the elements that stimulate plant growth,

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and pasture lands contribute organic wastes and intestinal bacteria. These contributions are sometimes called "natural pollution." Whether the origin is natural or from a sewer outlet, the stimulatory effect upon organisms is the same in principle. The recognizable result is that the unpolluted stream supports a variety of organisms as a normal biota.

EFFECTS OF POLLUTION ON BIOLOGICAL ENVIRONMENT

The entry of pollutants changes in many ways the conditions under which stream organisms normally live. This discussion can consider only a few, but there are changes in the stream bottom, in the physical and chemical properties of the water and in the competitive relations of organisms.

Sewage is a complex mixture of many kinds of substances that have been discarded by man because, to him, they have no further value. The constituents are organic and inorganic, simple compounds and complex ones. The organic substances include carbohydrates, proteins and fats as well as their decomposition products. There are salts of various kinds including ammonium salts, nitrates and nitrites. Organic growth stimulators also are a part. Some of the sewage substances are in solution, some colloidal and others suspended but capable of settling. It follows, then, that a recipient stream will have its waters affected by all fractions of the sewage while the stream bed is altered primarily by settling particulate matter.

If the stream is represented graphically (Figure 1) with mileage distances (or hours of flow) on the horizontal axis, the fictional community of Windmill is located at the zero level. Distances upstream are to the left and downstream to the right. The intensity of varying environmental conditions is plotted along the vertical axis. Food for organisms -- chemists call this B.O.D. -- is shown as curve F. The introduction of sewage tremendously augments the normal supply and thus alters this environmental factor. As the food supply is increased by pollution, the bacterial population tends to increase in geometric proportion and draws upon the available food (Figure 4). It is to be expected that the food supply will decline downstream and will eventually approach the pre-pollutional value. This is found to be a fact.

All organisms require oxygen for the maintenance of life. When applied to food, it functions in releasing the life-supporting energy that foods contain. Man draws upon the atmospheric supply by breathing, while most aquatic organisms draw upon the oxygen dissolved in water. Bacterial reduction of the pollutional food supply -- desirable and necessary as it may be -- is not accomplished without cost. That cost is reduction in dissolved oxygen concentration beyond the point required by desirable water animals.

The normal oxygen value of clean water is shown as areas A, from this level to 40 per cent of saturation as B, lesser concentrations as C, and those increasing beyond 40 per cent of saturation as D. These areas also mark the arbitrary limits of stream zones based upon oxygen concentration. The descriptive names are <u>clean water</u> for <u>A</u>, <u>degradation</u> for <u>B</u>, <u>active decomposition</u> for <u>C</u> and <u>recovery</u> for <u>D</u>.

If the pollutional load is fairly light or the dilution factor high, the sag curve resembles the upper curved line with normal value reestablished at 58 miles. This is accomplished by addition of oxygen from the atmosphere and through the activity of green plants. Where the content of organic matter is sufficiently high, dissolved oxygen may be reduced to zero through the oxygen-absorbing efficiency of bacteria. This is the ultimate in organic stream pollution and the circumstance upon which the following discussion is based. This poorest of stream conditions will be discussed since conditions that are less severe are then readily apparent also.

Ten miles below Windmill is the beginning of a 20-mile zone in which dissolved oxygen is absent entirely.

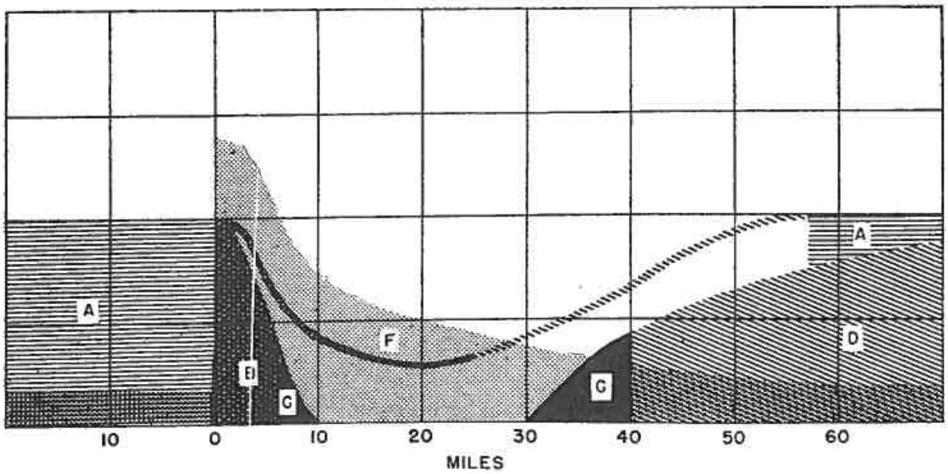

Figure 1 - Graphic representation of hypothetical polluted stream showing relationship of biotic food supply (F) and dissolved oxygen sag curve.

Here, the biotic demand for oxygen is greater than the supply provided by solution from the atmosphere. Bacteria and certain other organisms occupying this septic region are obliged to obtain the required oxygen from other sources. This they do by reducing oxygen-bearing compounds by anaerobic processes. Such activity may result in depleting the supply of oxygen found chemically in nitrates and nitrites, and reduces sulfates to hydrogen sulfide with its offensive odor and toxic action. These are some of the causes for rising gas bubbles and sludge in the septic zone. The gases alone make living conditions here unattractive for most forms of life.

Stream environment is further affected by the suspended semi-solids of sewage (Figure 2-A). These affect green free-floating stream life by immediately decreasing the transparency of the water and blotting out the sunlight. Downstream from the sewer outlet the water is turbid and slightly brownish, becoming dark and murky in the septic zone. As oxygen is added downstream by reaeration, the water gradually clears and finally is tinged with green by suspended microscopic plants.

Organisms that live in the stream bed are also affected by the suspended matters of sewage. These finally settle to the bottom (Figure 2-C) as a blanket of debris that effectively covers the normal habitat of clean water bottom life. It is an inexhaustible source of food but will sustain only those organisms that can qualify for life in that habitat. They must be efficient in obtaining oxygen, for conditions frequently are anaerobic. They must be able to burrow and creep so as to stay on top of the steadily growing layer, or else must be indifferent to being covered over. They must resist the toxic action of hydrogen sulfide and other gases that may emanate continuously from the deeper sludge layers.

Thus, it is seen that sewage alters the normal conditions of food supply, dissolved oxygen, turbidity, bottom surface, and chemical character of the stream and its bed. These are but a few of the environmental alterations that result from sewage pollution. They are sufficient to show that biological changes are sure to follow. Alteration in the competitive relations of stream life will be shown in subsequent discussion.

ACTION OF ORGANISMS UPON THE POLLUTANT AND THEIR RELATED DISTRIBUTION

It is apparent that most modern methods for the treatment of sewage depend, at some stage or another, upon the activities of living organisms. So much is this the case that all sorts of schemes have been devised for pampering the biotic associations and fostering their work. Biological competition is removed in the wastage of activated sludge, and oxygen is supplied to excess. The trickling filter brings the organisms food and oxygen and washes away their metabolic wastes and products. In the sludge digester, they are kept warm so their work proceeds properly and at a rapid pace. In the final analysis, the modern treatment plant is an artificial, telescoped, polluted stream with the zone of degradation at the primary tank and the recovery zone in the final effluent. The high efficiencies obtained are related entirely to these artificial stimulatory conditions, for the fundamental biological processes are the same as in the less efficient stream.

It has been shown that sewage is food, stimulation and habitat for simple forms of life, and that reduction in the organic stream load is accompanied by a corresponding extraction of oxygen. It is not the intent of this discussion, nor within the ability of the writer, to give in detail the precise bacterial activities involved in this accomplishment. At the same time, the basic information is important and needs consideration.

The millions of bacteria in sewage-laden waters are of a variety of kinds and have a variety of abilities. Some of these are normal inhabitants of both clean and

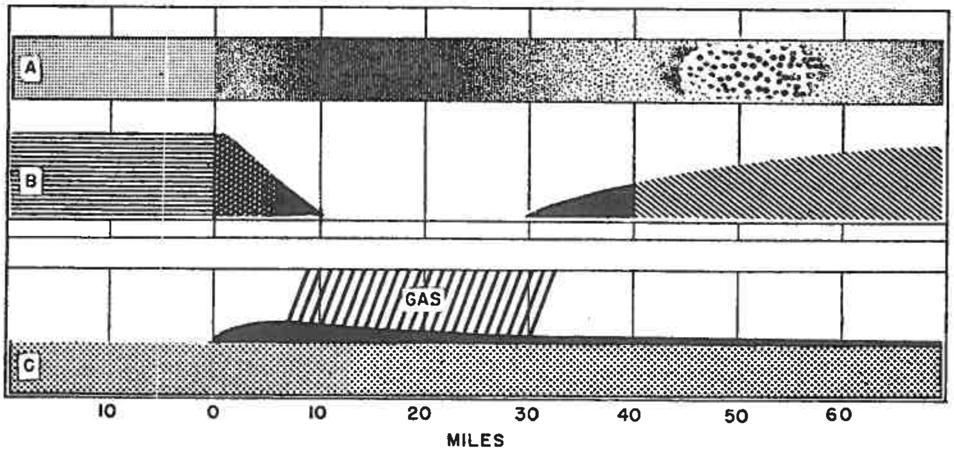

Figure 2 - Biotic habitat alterations resulting from stream pollution. (A) Physical changes in water resulting from entry of raw sewage at zero mileage level; (B) dissolved oxygen sag curve; and (C) accumulation of bottom sludge deposits and rising gas bubbles.

foul water. The presence of sewage stimulates their population increase (Figure 4). Others find their way into the stream in tremendous numbers as normal inhabitants of sewage. Some bacteria are able to multiply in the stream, while others such as B. coli and disease producers appear to die off gradually downstream. They may starve to death, be eaten by predators, be killed by high acidity, or disappear in still other unknown ways. In any event, the population peak is in the near downstream vicinity of the pollutional source.

Some bacteria can act upon a given organic compound, derive energy and growth material from it, and leave an altered residue that serves a different bacterial species or other organism in the same manner. In this way, chains of progressive actions are set in motion that result eventually in the transformation of sewage to simpler, innocuous substances. Some of these are carbon dioxide and water from carbohydrates and fats, and salts of phosphorus, sulfur and nitrogen from protein. Evidence of this mineralizing process is found in the progressive quantity shift from organic nitrogen, to ammonia, to nitrites and finally to nitrates as the water proceeds downstream.

As bacteria grow and multiply, selected constituents of the sewage are incorporated into their living substance. The ability to do this distinguishes all nonliving from living matter. It is an important ability, for in its practice a part of the sewage is set aside momentarily for action at a later time. On this account, bacteria sometimes are called concentrators of the pollutional load.

These activities of bacteria proceed in all parts of the stream. They are distributed throughout the water and are mixed into and over the bottom deposits. Under conditions of intense pollution, dissolved oxygen eventually is depleted in the flowing stream. Such depletion is more frequent and widespread in the bottom sludge. When this condition prevails, as from the 10 to 30-mile levels in the illustrative stream, bacterial action becomes of a different sort. In this septic region bacteria that are able to do so, act upon oxygen-bearing compounds in such a manner that oxygen from outside sources is not required. These bacteria are commonly called anaerobes. Their actions are to be prevented, if possible, for their products are various acids and such gases as ammonia, methane and hydrogen sulfide. Living conditions here are suitable only for organisms unaffected by these products and indifferent to oxygen supply.

Biological action in the stream continually decreases the food supply so that at 50 to 60 miles the concentration approximates the upstream values. Bacteria decrease in much the same pattern so that normal populations are attained at about the same level.

In addition to bacteria, unpolluted streams support a variety of other kinds of organisms. Those forms that produce their required food from minerals, carbon dioxide and water are members of the plant kingdom. Animals are those that require a supply of food already prepared. Bacteria and molds resemble animals in their food habits, but are classed as plants that lack the ability to make food. Organisms may be classified further by their position in the stream. Those that are small, suspended in the water and swept along with the current, are called the plankton. Plankters may be either plant or animal. Organisms that are attached to, lie upon, creep over or burrow into the stream bed are called the benthos. As has been stated, the bacteria occupy all of these positions. Large animals such as fish, frogs and turtles are not considered in this classification scheme.

Clean waters support a wide variety of organisms consisting of plant and animal plankton as well as benthic organisms. They are exacting in their habitat requirements and are affected by any interfering alterations. Normal changes in temperature, light, dissolved oxygen and food supply tend to result in shifts in the population picture. These, however, are rarely great, for predation, death and growth moderate the changing tendency and keep the biotic society in balance. In this society are organisms ordinarily associated with clean stream conditions. Some of these are game fishes such as trout, bass, blue-gills and pike, and smaller animals such as mussels, crayfish, snails and the larvae of caddisflys, stoneflies and dragon and damselflies. Shrimplike scuds may be present, swimming about on their sides or climbing over vegetation. A complete list of these organisms would be a long one.

In such a list of inhabitants would be the names of some organisms that are just holding their own, never building an appreciable population. Competition is too keen, food supply too low, and the habitat not quite suitable. Some of these would fare better in the polluted portions of the stream.

SIGNIFICANCE OF BIOLOGICAL POPULATION

The remainder of this discussion is based upon the principle that organisms differ, not only in appearance, but also in their power of response to conditions of the environment. If all moderating factors for a given organism are removed, the organism will thrive and produce tremendous numbers. On the other hand, if environmental factors are inhibitory, numbers will be small or totally absent. A set of conditions that are ideal for one organism may be lethal for another.

If changing conditions, such as pollution, are unfavorable, organisms must resist these changes, migrate or be destroyed. But, if conditions are favorable for certain organisms, these will thrive and build high populations. For this reason, the society of organisms found in zones of pollution is highly significant. It offers clues to the intensity of pollution and the degree of recovery.

Let it be supposed that the clean waters of the illustrative stream will provide suitable living quarters for a hundred different kinds of organisms, -- a balanced society of plant and animal species (Figure 3-A). With the entry of sewage, the variety decreases rapidly. Of these 100 species upstream the majority find conditions for life unsuitable in the zones of pollution. It is only downstream in the recovery zone where biotic variety makes a gain.

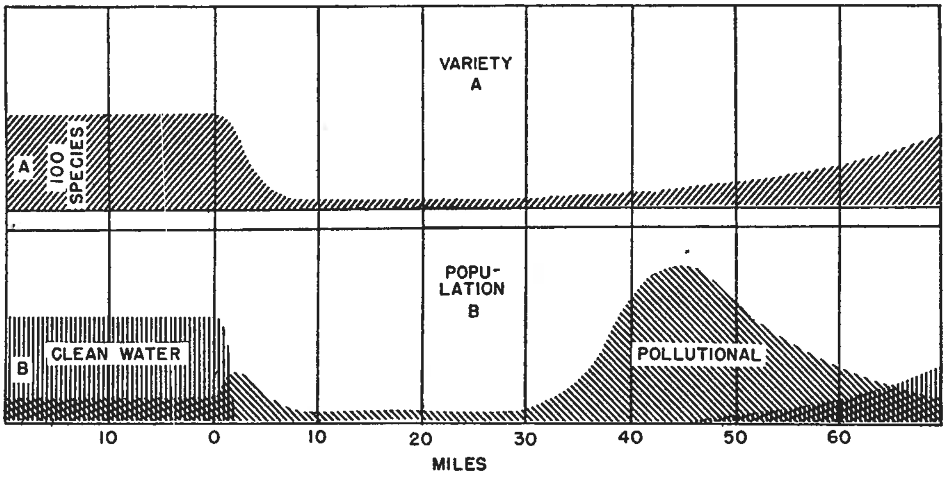

Figure 3 - Responses of bottom organisms to entry of raw sewage at zero mileage level. (A) Varity distribution; (B) population alterations of "clean water" and "pollutional" bottom forms.

Strange as it may seem, these few species in the pollutional zones find conditions quite suitable. Here they thrive in the absence of competition and with a high food supply. They are the ones that are intimately concerned with stream recovery. They may be called pollutional organisms.

If the biotic population be differentiated into clean water and pollutional organisms (Figure 3-B), their distribution may be contrasted. Bacteria are excluded from this graph. Clean water population drops abruptly to zero with the introduction of sewage. The population increases downstream with the variety increase. Pollutional population is low in clean water, but response is quick in the presence of wastes. Even these organisms decline in the true septic zone where only the anaerobes can live. The population peak will occur near the 45-mile level where food is abundant and oxygen again sufficient for the biotic needs. In the absence of a septic zone, both population peaks would roughly coincide. This condition will apply also in the following graphs. Population drop from the 45-mile point reflects approaching exhaustion of the food supply.

POLLUTIONAL ORGANISMS AND THEIR FUNCTIONS

Swimming about among the bacteria and creeping over the bottom sludge are minute animals composed of a single structural unit or cell. Some of these are able to utilize complex dissolved and particulate organic substances and in this way parallel the action of bacteria. Their prime function, however, is a more important one. They drive the bacteria and keep them at work. This is accomplished by the simple expedient of voraciously eating the bacteria so that they must reproduce to maintain their numbers. Since growth is a prelude to reproduction, biochemical oxidation proceeds at a feverish pace.

The bacteria-eaters are mainly those protozoans equipped with cilia which they use for swimming and food gathering. They move about continuously, lashing the water with their cilia and setting up currents that sweep bacteria into the gullet. This practice is carried out wherever bacteria occur. Following due process of ciliate digestion, the bacterial substance is now protozoan substance. The presence of bacteria and organic supplies results in a population peak below the bacterial peak as well as one above the septic zone (Figure 4).

But, for these protozoans all is not sublime -- they too have enemies. As they are swept downstream or flutter over the mud, they finally fall victim to rotifers, water fleas and related crustaceans that select them for variety in their diet of bacteria and small algae. The peak crustacean population is at the 58-mile point (Figure 4). And so it goes, the larger eating the smaller until the food progression leads to mussels, crayfish, small fish and large fish.

Mainly restricted to the bottom is another array of biotic forms. These are perhaps the most dependable indicators of stream condition. Ordinarily, the pollutional bottom is a confusion of biological activity -- each member of the assemblage going about his own business of gathering food and reproducing. To them, stream recovery is merely incidental. The distribution of species is governed by the stringency of habitat conditions.

Rat-tail maggots (Figure 5-A) are a sign of extremely poor conditions. Thus ugly larva of the dronefly (Eristalis tenax) lies buried in the mud with the tail extended to the surface for air. For this reason, dissolved oxygen is not a consideration and it may penetrate into the septic zone.

Next in line come the sludge-worms (Tubificidae) (Figure 5-B), reddish in color, 1/2 inch to 1-1/2 inch

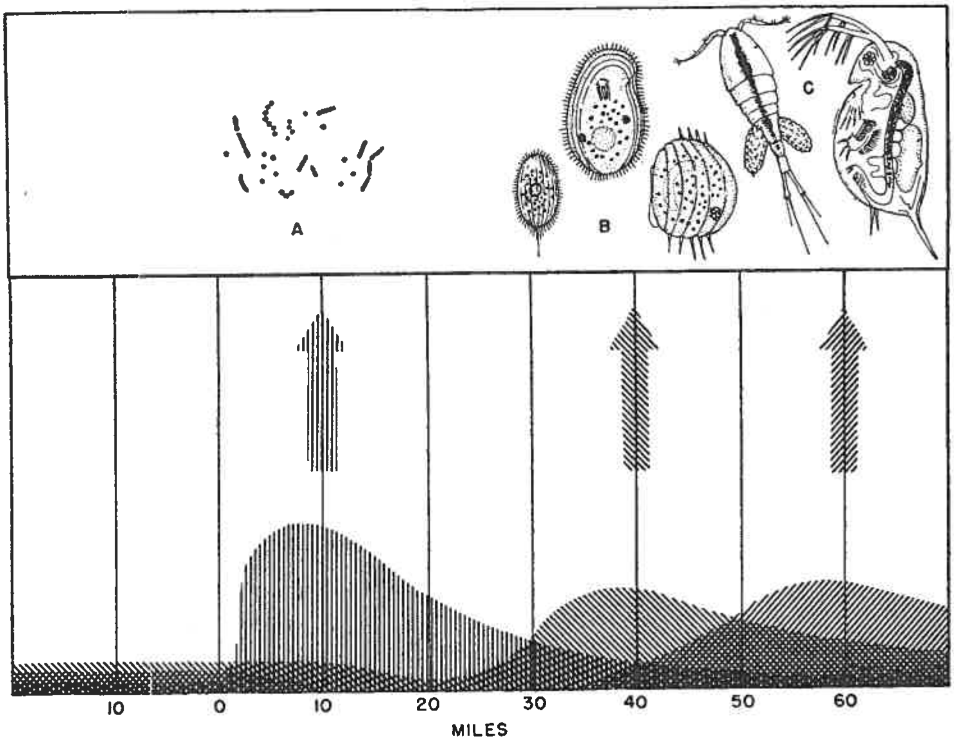

Figure 4 - Linear alterations in populations of bacteria, ciliate protozoans, and crustaceans.

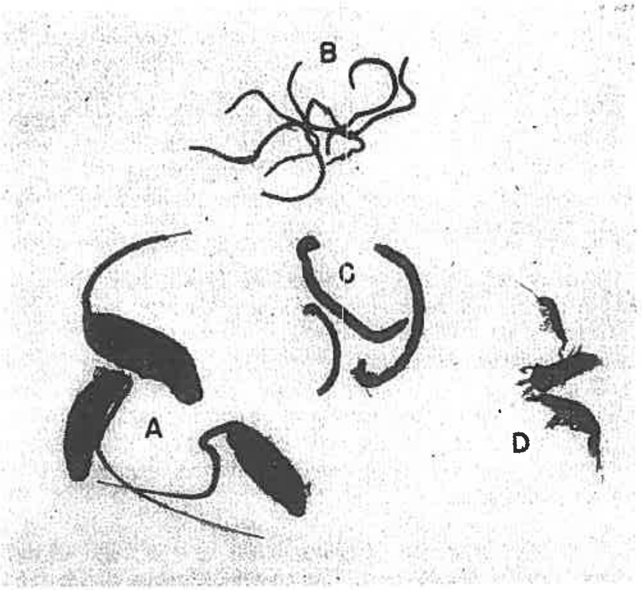

Figure 5 - Bottom organisms found in zones of pollution. (A) Rat-tail maggot (Eristalis tenax); (B) Sludge-worm (Tubifex sp.); (C) Blood-worm (Chironomus sp.); and (D) Sow-bug (Asellus communis). Approximately natural size.

in length. They burrow in the mud where organic content is high. They excavate in the upper layers of the sludge, passing large quantities through the intestinal tract and straining out the food. With the posterior part of the body projecting into the water, the worms cast rejected parts of the sludge on the surface in the form of fecal pellets. The work accomplished in this manner is tremendous. The sludge is worked over, perforated and its organic content reduced.

Frequently these worms are so numerous that the stream bed appears as a red undulating sheet. They occupy the zones of degradation, active decomposition and the upper part of the recovery zone. They are absent from the septic region.

Blood-worms (Chironomus sp.) also are burrowers in the mud. These are red, jointed, worm-like animals (Figure 5-C) that eventually transform to midge-flies. In this larval stage, they occupy burrow-like tubes constructed of sludge stuck together with an adhesive substance. Empty tubes are common and may occur in heaps. Their food habits are similar to the sludge worms, but they are more exacting in their habitat requirements. For this reason they reach their peak in the recovery zone.

At this point, also, the sow-bug or water-log-louse (Asellus communis) makes its first appearance. They are flattened, greyish animals about 1/4 inch long

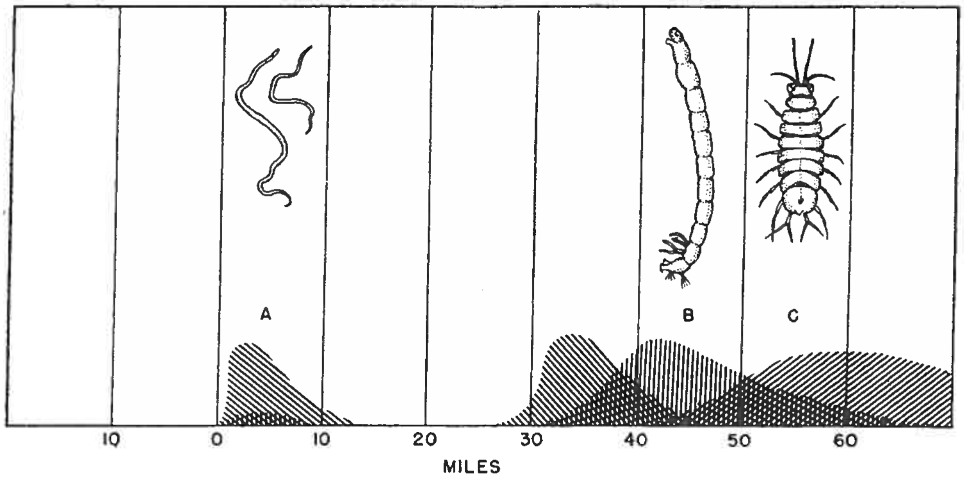

Figure 6 - Linear alterations in populations of sludge-worms (A), blood-worms (B), and sow-bugs (C).

(Figure 5-D), related to the scuds found in clean water. They are provided with jointed appendages, of which six pairs are modified as legs. They crawl about on the bottom, under stones, or climb among water weeds. They do not move by swimming.

Sow-bugs are omnivorous in their feeding habits but seem to prefer dead and decaying vegetable matter. Their oxygen requirements apparently are greater than those of sludge-worms or blood-worms. They are common in the recovery zone where dissolved oxygen in the supernatant water exceeds 40 per cent of saturation. They indicate improving conditions.

If the distribution of sludge-worms, blood-worms and sow-bugs are plotted together, their population peaks occur in the succession shown in Figure 6.

In addition to bacteria, other plants also are involved in stream recovery. Sewage molds and filamentous bacteria may be seen attached to sticks, stones and vegetation, waving gracefully in the current (Figure 7). They function with the bacteria in biochemical oxidation. They are whitish gray, becoming tinged with yellow, red or brown when old. In the zone of degradation, growth is widespread and luxuriant. It persists to the septic region and reappears feebly with

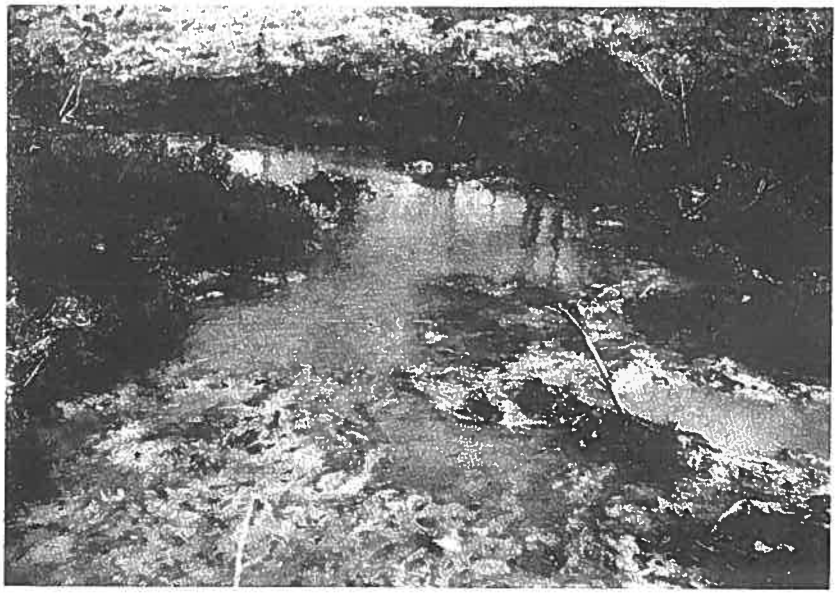

Figure 7 - Sewage mold (Sphaerotilus natans) attached to sticks, stones and vegetation and waving in the current.

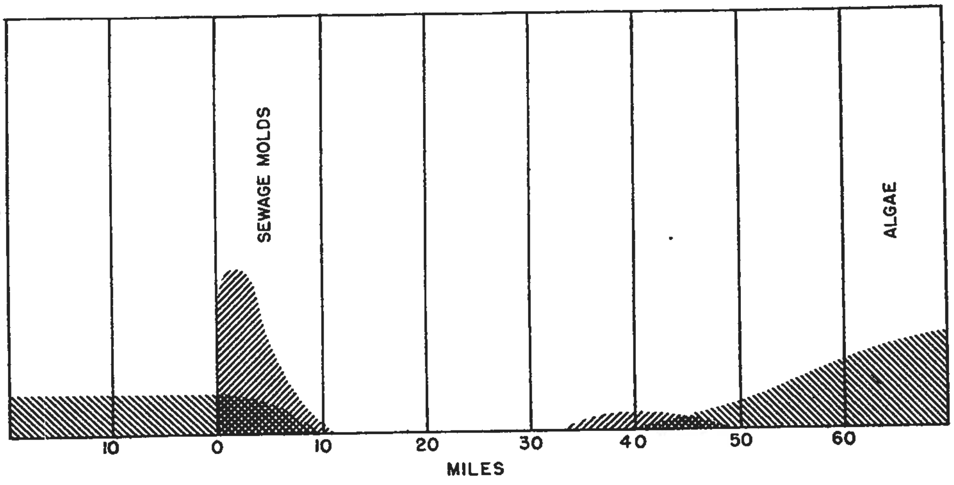

Figure 8 - Linear alterations in populations of sewage molds and plankton algae.

oxygen restoration. Its presence is a reliable index of intense pollution -- especially by carbohydrates.

The distribution of plankton algae, as a group, is in contrast to the sewage molds (Figure 8). The clean water population is reduced rapidly in the degradation zone where turbidity is high. They may be very sparse or absent throughout the septic region and then increase to a new high under the stimulatory influence of phosphorous and nitrogen compounds oxidized from sewage sources.

In the pollutional zones benthic algae may occur as a dark film over the bottom or as a bright green scum along the banks and in quiet spots. Most of these are filamentous, although some may be single-celled and able to swim. Some, at least, absorb certain organic solutions from the water. Valuable as this may be, the algae are more valuable for the oxygen they add to the water in the process of making food. They are instrumental in drawing up the lower end of the sag curve. They supply oxygen for the biochemical demand and speed the recovery process.

SUMMARY

Living organisms are affected by the conditions of stream pollution. Their distribution is altered and may be used to complete the pollutional picture obtained by the usual testing procedures. Their activities contribute tremendously to stream recovery by using pollutants as a source of energy and growth material. Some eat bacteria and thus accelerate their biochemical activities. Green organisms supply oxygen so greatly needed for B.O.D. satisfaction and sag curve elevation. Metabolic wastes, products and dead bodies are passed back to the stream as an altered link of a continuous chain. Biological efficiency in the stream falls far short of that in the treatment plant. A good treatment plant at Windmill would confine these activities and restore utility to the running stream.

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SOME IMPORTANT BIOLOGICAL EFFECTS OF POLLUTION OFTEN DISREGARDED IN STREAM SURVEYS

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The complexity of the pollution problem is being constantly intensified by the ever-increasing variety of pollutants that are added to streams. Due to the fact that pollutants, domestic and industrial, represent only a portion of the many factors which determine stream environments, the same pollutant may not bring about similar conditions in different streams. The character of the watershed, including soil type, amount and type of ground cover, and land uses; the amount, seasonal distribution, and type of precipitation; the frequency of floods and the amount of erosion; and the character of the stream banks, bottom materials, gradient and stream flow are all of importance. These and other factors determine stream characteristics, environmental conditions, the aquatic biota, and in large part the effects of different polluting substances.

SOME BIOLOGICAL EFFECTS OF POLLUTANTS

Pollutants may alter the stream environments and thereby affect aquatic life in a number of ways. These environmental changes may include an increase in stream temperatures; changes in the character of the stream bottom; increase in turbidity; changes in the content of dissolved oxygen; increase in dissolved nutrients; production of undesirable growths; deposition of sludge beds; and the addition of toxic wastes. The degree or extent of the effect of these changes on aquatic life varies with the type and amount of the pollutant and the character of the receiving water. It is the purpose of this paper, therefore, to point out some of the possible effects of pollution on aquatic life and to indicate pertinent ecological conditions which should be noted in stream surveys.

Water used for cooling purposes in industrial processes may become so hot and be of such quantity that it may substantially raise the temperature of the receiving stream. The addition of a waste or wash water having a fairly constant temperature tends to stabilize stream temperatures, especially during the winter (31) and may increase productivity through increased metabolic activity. Moderate heating by increasing metabolism can hasten the natural purification process and shorten the pollutional zones (56). In trout streams even a slight rise in temperature is usually undesirable (6). Due to the removal of shade and other factors (73) (64), many trout streams are approaching borderline temperatures (87) and a rise of even two to three degrees Fahrenheit sometimes is sufficient to eliminate trout or to make the stream less favorable for them (6). If temperatures become too warm for trout on only one day in the year, that stream ceases to be a trout stream (47). Highest stream temperatures during the day usually occur between 2 and 4 p.m. and peak temperatures usually occur after a succession of warm days and nights. Few trout, even the most tolerant species, can survive temperatures above 82 to 83 degrees Fahrenheit even for very short periods (44) (24). During the summer of 1930, the senior author found rainbow trout living in the South Branch of the Pere Marquette river in Michigan at a peak temperature of 83 degrees Fahrenheit. This temperature occurred for a short time between 3 and 4 p.m. During July, 1931, brook trout survived peak temperatures of 81 and 82 degrees Fahrenheit in the East Branch of the Black river in Michigan.

Studies of trout streams in many portions of the country and observations on the effects of the removal of shade and the raising of stream temperatures has lead the senior author to conclude that water temperatures need not be raised to lethal levels in order to affect trout populations adversely. When stream temperatures are raised so that they consistently exceed 70 degrees Fahrenheit in summer, environmental conditions become less favorable for the cold water species and more favorable for the warm water forms (6). Due to this change in environmental conditions, minnows, suckers, and other warm water fishes may increase in numbers at the expense of the Salmonoids (87) which decrease in numbers to such an extent that sometimes they represent less than ten percent of the total fish population (43) (69).

Fish population studies conducted by the senior author in 1931 and 1935 in the East Branch of the Black river in northern Michigan, indicated that trout comprised 9.6 percent of the total number of fishes and 8.6 percent of the weight of the total population of fishes. Minnows, however, accounted for over 60 percent of the total number of fishes taken and made up 9.6 percent of the total weight of the population. Suckers comprised 23.3 percent of the total number of fishes and 66.7 percent of the weight of all fishes. Studies carried out in 1934 on another warm trout stream, the Pigeon river, indicated that the trout comprised 14.3 to 19.7 percent of the total population; whereas minnows comprised 58 to 68 percent of the population. Fish population studies made during the same period on a cold stream, the West Branch of the Sturgeon river, which lies near to and parallels the Pigeon river, indicated that in the latter stream trout comprised 93.8 to 98.7 percent of the total number of fishes and over 99 percent of the total weight of the population. Shetter and Hazzard (67) found that in the lower portion of the South Branch of the Pine river of Michigan, where the water is fairly warm, trout comprised 13.6 percent of the population, while in a cold stream, the Little Manistee river, they comprise 64 to 91 percent of the population.

In streams inhabited by the warm water species, sunfishes, white bass, black bass, crappie, etc., a slight rise in temperature may increase productivity (78) (33). Temperatures directly lethal to fishes are not so likely to occur in such streams. In the northern portion of the country, bass have been killed by water temperatures of 94 degrees F. (Michigan Lake 1936). In the TVA Reservoirs of northern Alabama water temperatures sometimes reach 96 degrees F. without apparent harmful effects to bass and other native fishes. Near Savannah, Georgia, all fish in a shallow pond died in water which reached 108 degrees F.

The type of bottom material directly affects the productivity of a stream. Shifting sand bottom streams are virtually aquatic deserts (74) while rubble gravel bottoms usually support large populations of aquatic insects (75) (76) (77). The addition of sand, clay, or other inorganic wastes which covers more productive bottom types is, therefore, detrimental to the overall productivity of a stream.

Inert inorganic wastes may be added to streams from a number of sources such as hydraulic and placer mining operations (68), mine tailings, gravel pit washings (89), etc. However, the greatest and most widespread sources of this type of pollutant is soil erosion (7) (17). During the past century floods and soil erosion have been greatly increased in some areas by deforestation (5) (14), fire, overgrazing (30) (41), and ill-advised agricultural practices (34) (86). Materials eroded from the watersheds and washed into streams affect the aquatic environments in a number of ways (48). Sand and silt fill pools, destroy fish cover and spawning beds (35), and cover productive bottom types (45) (46) (52). Erosion and eroded materials have converted good fish streams into wide washes where the low water flow meanders over the wide bottom in a thin sheet or disappears completely in the deposits which choke the former stream channel.

Eroded materials also cause turbidity which affects productivity and water uses. Turbidity decreases light penetration and thereby limits the growth of phytoplankton and other aquatic plants which are of outstanding importance as a basic food for aquatic animals and as a producer of oxygen by photosynthesis (49). The photosynthetic activity of aquatic plants plays an important part in stream reaeration and in the natural purification process (10) (55) (60). Although turbidity prevents or limits algal growth, it does not eliminate the bacterial action which mineralizes organic wastes (13). Thus, turbid waters may transport the bi-products of bacterial action on organic wastes and the effluents of sewage treatment plants considerable distances before they are utilized (83). When the water clears due to impoundment or other causes so that the phytoplankton can grow, these fertilizing materials are utilized and may produce troublesome blooms, or taste and odor problems far from the source of pollution.

Soil washings from eroded areas are usually infertile and generally reduce productivity by choking or covering densely populated rubble gravel riffles, and rich bottom deposits. Washings, from fertile areas, where accelerated erosion is just beginning, or from rich well-fertilized agricultural areas, carry a great deal of nutrient materials into lakes and streams and increase productivity. This fertilizing effect may be so great that nuisance blooms of algae may develop each year such as those that occur in many Iowa lakes. These blooms become especially troublesome when domestic sewage is also added to the water (9) (40). Further, in some areas, blooms of toxic algae are frequent and severe (8) (50).

The sole detrimental effect of putrescible wastes is often considered to be oxygen depletion. Putrescible wastes, however, may affect environmental conditions, aquatic life, and water uses in a variety of ways. Organic wastes serve as nutrients which stimulate growth and reproduction of aquatic life (10). The first group to be stimulated are the bacteria which are chiefly responsible for the decomposition and conversion of organic wastes into nutrient materials such as nitrate, phosphate and carbon dioxide (16). If the organic materials occur in sufficient concentration the bacteria may utilize nearly all of the dissolved oxygen and produce conditions which are unfavorable for many other forms of life (9). When such conditions prevail the zone of greatest bacterial growth is designated as a septic zone, in which the species of macro-invertebrates are limited to those organisms that have the ability to live under low oxygen concentrations and those which have adaptations for breathing atmospheric oxygen (3) (31). Although the number of different species of macro-invertebrates occurring in the septic zone, is only a fraction of the number found in the other well-recognized zones of pollution, productivity from the standpoint of numbers and volume of organisms produced is several times that of the other zones (4) (12) (31) (63). This is well-demonstrated in Figure 1 which shows the number of different species and the number and volume of organisms found per unit area under summer conditions in the various pollutional zones of Lytle creek, a small stream near Cincinnati, Ohio, which has been intensively studied by the Public Health Service. This small number of species and very large number of individuals constitute a biological indication of septic conditions (59).

The decomposition of organic wastes by the bacteria converts them into materials such as carbon dioxide, nitrate, and phosphate, which are readily used by phytoplankton. As these materials become available,

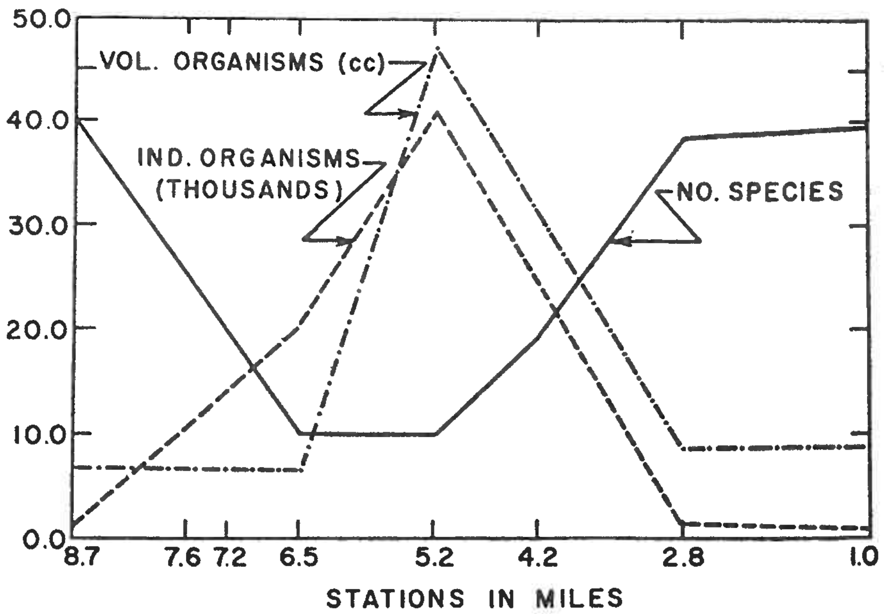

Figure 1 - Macro-invertebrate distribution, Lytle creek, summer conditions.

there is a gradual buildup of phytoplankton in the lower septic zone which reaches its peak in the recovery zone (28). Considerable oxygen is produced by the phytoplankton when conditions are favorable (60). Investigations carried out at the Cincinnati station of the Public Health Service have demonstrated that in many small and moderate sized streams which are fairly clear, reoxygenation by photosynthesis completely overshadows reoxygenation by aeration. Because of the large amounts of food present in the recovery zone of streams polluted with putrescible wastes, phytoplankton populations may become very large and dissolved oxygen levels frequently may exceed saturation by 100 percent (31) (56) (60) (61). In fact, a superabundance of dissolved oxygen may be an indication of organic pollution.

Because photosynthetic activity is dependent upon sunlight there may be wide variations in dissolved oxygen in a polluted stream during the 24-hour daily cycle (31) (38) (60) (66) (70) (84). Dissolved oxygen concentrations are usually highest between 2 and 4 p.m. and are lowest just before or after sunrise. At one station on Lytle creek, dissolved oxygen varied from a high of 19.4 p.p.m. in the afternoon to a low of 0.7 p.p.m. the next morning. The Lytle creek investigations showed that these daily variations in dissolved oxygen are greatest in the late spring and summer seasons and that the difference between maximum and minimum levels is most marked in the recovery zone. Nocturnal-dirunal variations in dissolved oxygen in Lytle creek at different seasons of the year are shown in Figures 2 and 3. It is apparent from these graphs that the season greatly influences minimum oxygen levels.

Year-round studies in Lytle creek and the Great Miami river have indicated a fairly definite seasonal cycle of environmental conditions (31). During the winter months there was an abundance of dissolved oxygen throughout the streams with levels at no time falling far below saturation. During spring as the water becomes warmer, oxygen was depleted just below pollution outfalls during the early morning hours. As the season advanced this oxygenless area increased in extent and duration until in late summer there was a definite septic zone in which oxygen was absent or essentially absent at all times. In Lytle creek there was an almost equal stretch of stream just below this zone in which oxygen was absent or very low during the night. As the fall season advanced the oxygenless zone decreased in extent and duration until by the beginning of winter there was an abundance of oxygen throughout the stream. Character of flow is of great importance in determining the seasonal pattern of stream conditions. If flows are extremely low in winter, septic conditions may persist into December, while if they are high they may not develop in summer.

It will be noted in Figures 2 and 3 that the greatest variations in dissolved oxygen occurred during the spring and summer in the zone of recovery and that concentrations of dissolved oxygen reached a maximum in that zone. These conditions prevailed because, first, phytoplankton growth and photosynthesis reached a peak in the recovery zone, and second, under conditions of supersaturation, riffles and general stream turbulence in the clean water zone brought about the release of oxygen rather than the absorption of additional amounts.

The decomposition of putrescible wastes either by natural purification or by sewage treatment provides a supply of those materials which stimulate the growth of large populations of phytoplankton (10) (28) (91). These algal populations through photosynthetic action aerate the stream and at times produce supersatura-

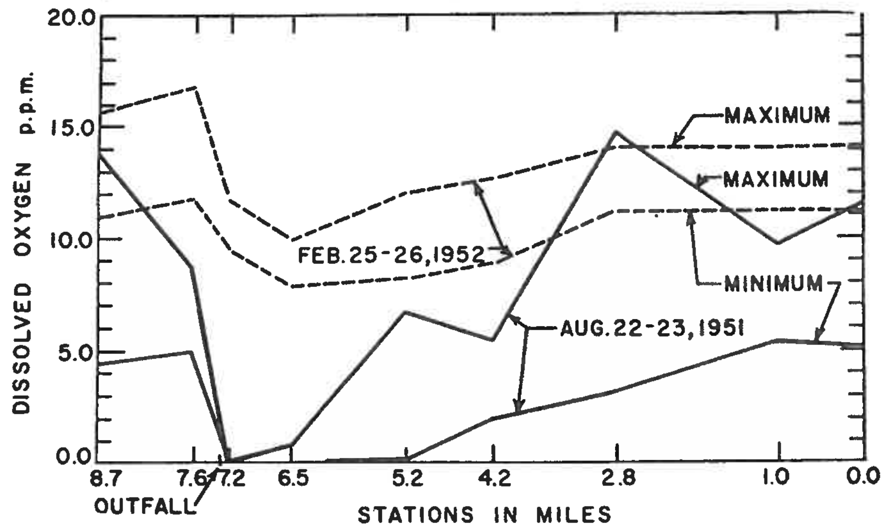

Figure 2 - Range in dissolved oxygen, Lytle creek.

tion (31) (49) (84). There is, however, a point, not definitely known as yet, beyond which the algae cease to be beneficial and may actually be harmful. This is due to the fact that at levels of supersaturation photosynthetic oxygen in streams is rather rapidly released to the atmosphere and this rate of release increases in proportion to the rate of production. Further, while the phytoplankton may produce large quantities of oxygen during the day (61), it also uses oxygen for respiration at all times and during the night excessively large phytoplankton populations may deplete the dissolved oxygen and cause fish kills (49) (54). Such a fish kill occurred in Lytle creek in the fall of 1952. At that time due to extremely low flows of clear water the nutrients in the stream caused an excessive phytoplankton bloom which produced dissolved oxygen levels in excess of 21 p.p.m. in the afternoon but during the night reduced dissolved oxygen levels to such an extent that a severe fish kill occurred in the recovery and clean water zones. It is possible, therefore, for a large secondary sewage treatment plant, located on a small to moderate sized stream, to indirectly cause fish kills through the production of nutrients which bring about excessive growths of algae which in turn deplete the oxygen at night by their respiration and decay.

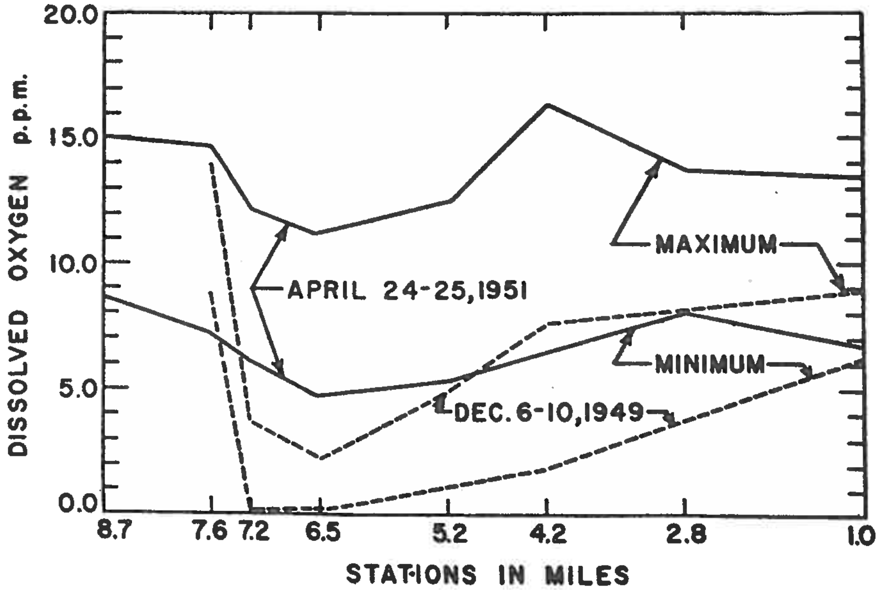

Figure 3 - Range in dissolved oxygen, Lytle creek.

These algal blooms may have other undesirable effects. The algal growths may cause tastes and odors in water supplies farther downstream (93), they may clog filters, or they may create toxic conditions at points of concentration (26) (49) (51) (92). The constant addition of even low levels of nitrogen and phorphorus, no greater than those which may occur naturally, can greatly stimulate algal growths (32). Under natural conditions available phosphates and nitrogen are rather rapidly utilized and bound up in the bodies of the phytoplankton. Studies made by Wiebe (personal communication) in Norris Reservoir, Tennessee, for example, indicated that all of the available phosphorus was utilized in the upper half of the reservoir. In reservoirs, nutrients are also removed by the dying and settling out of the plankters (90). If there are periodic floods which bring in silt that covers the dead organisms which have settled to the bottom, fertility is permanently removed from the reservoir. However, if they are not covered with silt and stratification occurs in the reservoir, they may be decomposed by bacterial action and the nutrient materials may be recirculated throughout the reservoir by the spring and fall overturns. In lakes which are stratified, this is considered to be a basic cause of the spring and fall peaks in plankton growths (90). Reservoirs may, therefore, remove or create problems, depending on conditions. Their mode of operation also influences downstream conditions (83).

In streams severely polluted with organic wastes the stream bottom in the septic zone is usually covered with grayish growths commonly referred to as "sewage fungus" (58) (91). These growths are often regarded as being a result of oxygen deficiencies because they are generally limited to septic areas during the season in which stream surveys are most often conducted. It has been shown, however, that these prolific growths are not produced by oxygen deficiencies but by concentrations of organic matter, chiefly nitrogenous and carbohydrate material (11). The low oxygen concentrations usually associated with them are incidental and the result of the decomposition of the organic material upon which they are dependent for existence. The common designation of these growths as "sewage fungus" is somewhat unfortunate because, while they may contain some fungi such as Geotrichum, Leptomitas, and Fusarium, they are often chiefly composed of the bacteria Sphaerotilus, Zoogloea, and Beggiatoa, and certain ciliated protozoans such as Vorticella, and Carchesium (11) (59). Taken collectively these organisms constitute a pollutional blanket which influences natural purification and other stream life in such ways as the breaking of the natural food cycle in the stream and creating an unfavorable bottom condition.

The year round studies which have been carried out on Lytle creek have demonstrated that when floods are not too severe during the winter months, there is a downstream extension of this pollutional blanket. This is brought about by a change in environment conditions which are more favorable for such growths; namely, an increase in the organic content in the water in the lower zones (36). This increase of organic matter further downstream in winter is believed to be chiefly due to two factors, first, a reduction in the time of flow to about one-fifth that of the summer period due to larger flows, and second, to low water temperatures which decrease metabolic activity of the bacteria and thus the rate of decomposition of the organic matter. The down stream extension of the pollutional blanket covers the bottom and alters the habitat so that it is unfavorable to most of the macro aquatic invertebrates which normally occur in the recovery and upper clean water zones, with the result that they must migrate or die. Its direct effect on the larger forms was well illustrated by the fate of stoneflies, mayflies, caddis flies, and other insects which were washed into polluted sections of Lytle creek. These insects soon became so covered with growths that they were overwhelmed and smothered. The accumulations of these growths on some mayflies, stoneflies, dragonflies, and other insects which were taken under such conditions are shown in Figures 4 and 5. In these figures normal insects are included to enable comparison with those which have been covered with the growths. The pollutional blanket does not develop if severe floods occur during the winter period. It develops during periods of normal or low water and it is removed by the first flood. After its removal the area is practically barren of bottom life and some time is required for it to be repopulated.

Seining studies demonstrated that fish were forced downstream during the period of existence of the pollutional blanket. In fact, although dissolved oxygen concentrations were near saturation throughout Lytle creek during the winter months the fishless area was about twice as long as it was in the summer months. This movement downstream of the fish population was probably due to the destruction of their normal food by the pollutional blanket. It is evident, therefore, that oxygen depletion is not the only factor responsible for the creation of fishless areas in streams polluted with organic wastes.

In instances of organic pollution it is generally assumed that the critically low oxygen levels which occur in streams in late summer during periods of low flow and high temperatures most seriously affect the overall economy of the stream. While this is generally true it may not always be the case. Observations have indicated that in small streams under such conditions increased metabolic activity plus very slow flows have resulted in greatly shortened septic zones. Further, if the water is clear, reaeration due to the photosynthetic activity of the phytoplankton builds up oxygen levels in the recovery zone such that the fishless zone is at a minimum. In addition, low water and slack current allows the settling out of a great deal of material so that it is for the time being removed from the stream. However, the first real rise in stream flow usually picks up these sludge beds and may create a real problem. Studies on the Great Miami river indicate that the first high water after an extended low water period picks up sludge beds and carries them farther downstream with a resultant critical decrease in dissolved oxygen over a more extensive area than was previously affected. The harmful effects of the removal of accumulated sludge beds have been noted by several investigators (9) (59) (88). Forbes (27) noted fish kills in the Illinois and Rock rivers due to the flushing out of sludge beds

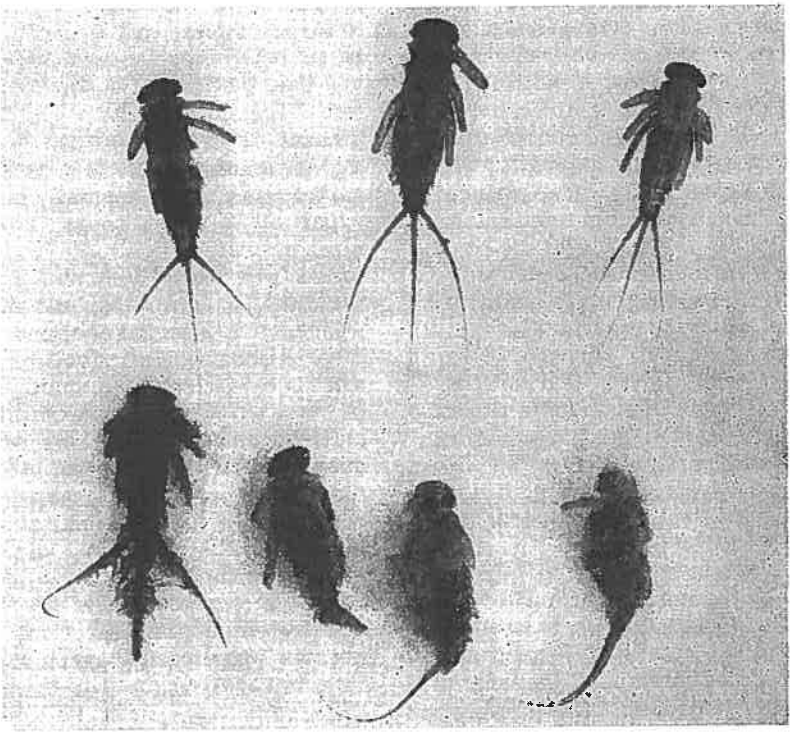

Figure 4 - Upper row, normal mayflies. Lower row, those which have been covered with "sewage fungus" (bacteria and protozoa).

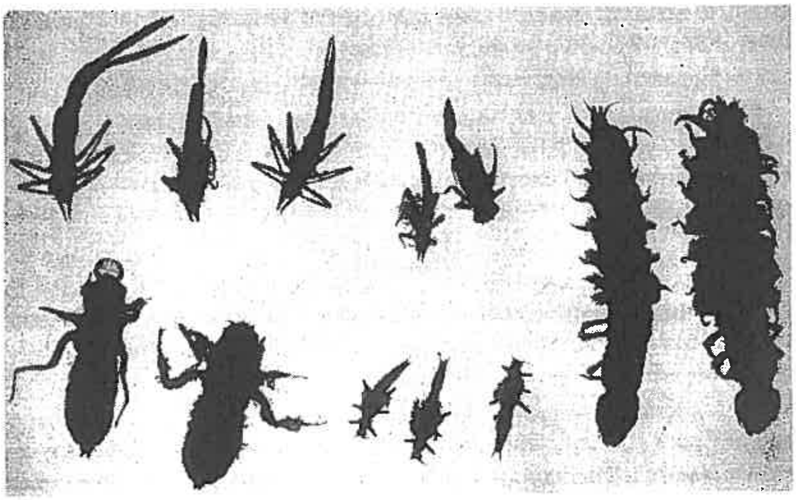

Figure 5 - Growths which develop on aquatic insects in polluted streams due to the downstream extension of the pollutional blanket (sewage fungus). Normal specimens are included for comparison. It can be noted how the gills are covered by the growth.

which had accumulated during periods of low water. The removal of settleable solids is, therefore, of value for the protection of stream life.

Toxic wastes may eliminate the fish population in certain areas or they may decimate only certain species or certain developmental stages. Thus, adults may migrate into an area and live where reproduction is not successful. Some fish food organisms are more sensitive to certain toxic materials than are fish (1). In such instances fish populations may be reduced due to lack of food without actually killing the fish. In addition to destroying fish, toxic wastes may interfere with the natural purification process by limiting those organisms which break down the wastes. If these wastes are to be controlled, their mode of action and their influence on aquatic life must be considered (19) (20) (22). Materials toxic to aquatic life can most readily be detected and their strength estimated by means of bioassays (21) (23).

The character of the water and its mineral content can alter considerably the toxic effects of a given chemical or waste (21). For example, an acid waste added to a highly alkaline stream may be much less toxic than it is when added to an acid stream (18). The reverse is true for alkaline wastes. Further, ammonia salts are much more toxic to fish at high pH levels while copper and other heavy metals are more toxic in soft acid waters. Antagonism and synergy are also of great importance. For example, it has been demonstrated that when salts of copper and zinc occur together they are several times as toxic as when they occur separately at comparable concentrations (84). It is evident, therefore, that the toxicity of wastes cannot be represented in chemical terms alone but should be combined with data secured by means of bioassays.

DISCUSSION

The foregoing has served to indicate that various types of pollutants may have a variety of effects on streams and their biota. Environmental conditions, which largely govern the natural purification process, vary widely in different streams. The capacity to assimilate and purify wastes and the rate of purification, therefore, is not a constant for all streams. Surveys designed to evaluate pollutional conditions and the ability of a stream to assimilate wastes must give full consideration to these environmental conditions.

While dissolved oxygen is of great importance it is only one of a complex of factors which constitute the aquatic environment. The species composition of the aquatic population in a given area is determined by the environmental conditions which have prevailed during the developmental period of the organisms involved (61). If at any time during its development, environmental conditions become lethal for a given organism, that organism will be eliminated even though the unfavorable conditions are of very short duration (9) (47). The aquatic population which occurs in a given area is, therefore, a representation or indicator of environmental conditions which have prevailed during the life history of the organisms comprising the population (3) (15) (53) (63). It is this property of indicating past environmental conditions, especially the extreme conditions of brief duration, that make aquatic populations such valuable indicators of pollution (25) (31) (42). In using biological indicators, however, single species do not possess high index value. Our Studies have indicated that it is the qualitative and quantitative composition of the population which is of importance in denoting past conditions. Further, the absence of clean water species is much more significant than the presence of tolerant species (31) (62).

Data on fish populations are especially valuable for indicating pollutional conditions because fish are the chief end product of the aquatic cycle. Data on the qualitative and quantitative composition of fish populations, rate of growth, average size, and catch per unit effort of the sport and commercial fishery are especially valuable for denoting the suitability of water conditions and the economic and recreational losses due to pollution. In fact the suitability of a water for fish life is best defined by its productivity.

Pollution affects fish populations in a number of ways depending upon the nature and concentration of the waste. Moderate amounts of organic materials which do not seriously affect dissolved oxygen levels, may serve as nutrient materials and increase fish production. This occurred in the Illinois river prior to 1920 (29).

Periodic fish kills due to spills attract a great deal of attention but they are, in general, much less harmful than the slow gradual increase in pollution which slowly decimates the population in such a way that the dead fish, or the decline in the fish population, are not noted and the fishery is destroyed without exciting public protest. In some streams in the east fisheries values have been gradually reduced over such a long period that the fishery potentials are not now generally realized (39).

Although extensive areas of streams are often made fishless the effects of pollution are not always on an all-or-none basis (62). The complete absence of fish is usually common information, but deteriorations in the quality of the population is not generally apparent without some sampling studies. In polluted streams the game fishes may be reduced in number or eliminated while the coarse species or those most tolerant of low oxygen concentrations comprise the remaining population (37). It has been the senior author's experience that when coarse fishes become abundant, they crowd out the game fishes which results in a marked decline in the sport fishery because the coarse fishes are not desired by the sportsmen and are inferior as food fishes (79) (80) (81) (82).

A somewhat routine procedure has grown up and been adopted for pollutional surveys. In these surveys, very often most of the effort is devoted to measurements of the discharge from various plants; to routine bacteriological, physical, and chemical studies of selected effluents; and to a compilation of existing data on domestic and industrial water uses, stream flows, sources of pollution, and sewage treatment. The physical, chemical, and bacteriological studies on the pollutants being discharged into the stream usually include determinations for D.O., B.O.D., pH, temperature, turbidity, settleable solids, total alkalinity, the coliform index, and others depending upon the nature of the waste discharged (2).

Sampling in the receiving stream is usually limited in scope and carried out during the period of low flow and high temperatures. It is customarily confined to the taking of grab samples at selected stations which are often highway bridges. Determinations made on these stream samples are generally the same as those made on the pollutional effluents.

All these studies can be worthwhile and are essential in many instances but their adequacy and value for meeting the overall problem would be greatly increased if some additional studies were made and a somewhat different approach were adopted. The collection, abstracting, rearranging, and assembling of existing data, the routine collection and analysis of samples, and the use of empirical constants and formulae may lead to a "cook book" approach to the overall pollution problem and the concept of the stream as a biological entity is lost.

Further, the routine application of the customary survey procedures can result in wasted time and effort. An example is the routine determination of B.O.D.'s and the coliform index for a waste, the detrimental effect of which is toxicity. Repeatedly, survey groups which go into the field to investigate one of the common biological effects of pollution, a fish kill, follow the customary chemical approach and carry into the field only equipment for the collection and analysis of water samples. Ordinarily no biological observations or studies are made. Further, when samples of the supposedly offending waste are brought into the laboratory an indirect approach is customarily used. First consideration is usually given to B.O.D. or oxygen consumed tests. When the possibility of toxicity is considered and the highly toxic materials, for which routine methods of analyses have been developed, are not found, little thought is given to the probability of the presence of those highly toxic materials which are not readily separated and measured chemically (19). If some of the more toxic substances are indicated by the analyses, their toxicity to aquatic life is frequently estimated on the basis of a limited knowledge of their toxicity in simple solution. Consideration is not given to the fact that the quality of the receiving water greatly influences their toxicity, or that they occur not alone, but in mixtures, and their action may be greatly modified by antagonism and synergy.

The simplest and most direct approach for determining toxicity which takes into consideration all these factors is to make a bioassay of the waste in question, using local species of fish as reagents and employing the receiving water for dilution of the waste. When bioassays are combined with chemical studies for toxicity determinations, much more progress will be made toward detecting, analyzing, and meeting toxic waste problems.

Considerable attention has been devoted to the development of procedures for estimating the dissolved oxygen levels that may be present at critical times of the year or during periods of recorded low flows. Customarily, the data on which these calculations are based are secured from grab samples taken without regard to photosynthetic activity and diurnal variations in dissolved oxygen (72) (85). When collecting data from the calculation of the sag curve attention should be directed not only to variations in water level, rate of flow, temperatures, and the character of the stream, but also to photosynthetic activity and the time of day during which samples are taken. From the standpoint of the protection of fish life, averages of dissolved oxygen concentrations determined from grab samples, are of little value and may be actually misleading unless the determinations on which the averages are based are taken at the correct times and minimal levels are known. It is the extreme and not the average conditions which are important.

Grab samples taken without reference to daily fluctuations in D.O. concentrations or the zones of pollution do not give an adequate or accurate measure of oxygen conditions in a stream. Further, in the calculation of sag curves, photosynthetic activity is neglected (71), even though in many streams it completely overshadows reaeration from the atmosphere and is at its peak during periods of low flow and clear water. In addition, much still remains to be learned concerning the effects of sludge deposits and the relation between the breaking down of the wastes under the controlled conditions in the B.O.D. test and what actually occurs in the stream. It has been shown that all wastes are not broken down at the same rate and that nitrification begins before the fifth day (65). The problem is not simply the amount of pollution discharged. It involves the fate of the waste materials in the stream under varying seasonal conditions, the capacity of the stream for handling that particular waste, and the effects on aquatic life of recreational and economic importance.

If environmental changes brought about in a stream due to pollution cannot be observed or measured, there is justification for estimating them inferentially. However, since the toxicity of wastes to fish life can be determined directly by bioassays, the direct effects of pollution on the aquatic biota can be determined by observation and population studies. Because the aquatic biota present in a stream or stream section serves to indicate past environmental or pollutional conditions, it is evident that the inferential approach is not always necessary. Since acceptable dissolved oxygen concentrations and regulations governing the discharge of toxic wastes are frequently set up to meet the requirements for fish life, and because the natural purification of putrescible wastes in streams is a biological process, the necessity of biological studies to supply pertinent information and to supplement and strengthen the customary stream investigations is apparent.

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BIOLOGICAL INDICES OF WATER POLLUTION WITH SPECIAL REFERENCE TO FISH POPULATIONS*

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A number of investigators have very recently published discussions having to do with biological indices and biological measures of water pollution (1) (2) (7) (13) (14) (15) (16) (26) (27) (28) (29) (30) (36) (38). Fjerdingstad (12) has discussed some of the pertinent European literature. The fundamental concepts presented by these authors are not original, for the idea that aquatic organisms can be useful "indicators" of environmental conditions, and particularly of the degree of pollution of water with organic wastes, has a long history (12). Because of certain novel features and the relatively wide scope of the studies, and the broad implications of some of the conclusions, the work of Patrick (26) (27) (28) (29) (30) has attracted much attention in the United States and seems to deserve the closest scrutiny.

Although much has been written about the various biological indices, there has been no general agreement among the authors as to the meaning of some of the most important terms used in this literature and little effort to clarify the terminology. In view of the variety of backgrounds and dominant interests of individuals concerned with waste disposal and with the effects of wastes on receiving streams, it is not surprising that the term "pollution" does not have exactly the same meaning for all. It is regrettable that a variety of meanings have come to be associated with technical terms such as "biological indicator of pollution". Some of the differences of opinion as to what the biological indices are and what may be their utility doubtless stem from a lack of agreement on the meaning of the word "pollution". Investigators proposing the use of different indicators of pollution should have clarified, it would seem, their ideas as to just what constitutes pollution, or, in other words, exactly what it is that the indicators can be expected to indicate. Too often this has not been done, or the ideas and definitions presented have not been carefully developed and appear to be unsound from a practical standpoint.

Should the mere change (physical, chemical, or biological) of some aquatic environment resulting from waste disposal be regarded as pollution even when ordinary human use and enjoyment of the water and of associated natural resources have not been affected adversely? When there is evidence of environmental change, is this always reliable evidence of damage to a valuable natural resource? May not certain beneficial uses of water be sometimes seriously interfered with by the introduction of wastes which may cause little or no detectable alteration of biological communities? Have there been any studies which have conclusively demonstrated a useable fixed relation between the biological indices of pollution and the actual fate or change in value of aquatic resources which are subject to damage by pollution? If water pollution can be the result of introduction of any of a great variety of substances, organic and inorganic, is it proper to refer to those biotic responses which are only known to occur in the presence of putrescible organic wastes (i.e. to organic enrichment of water) as "indices of pollution"? Can there be any general biological solution for all problems of detection and measurement of water pollution, or is effort being wasted in a search for such a general solution? Are broad limnological investigations being undertaken where intensive study and appraisal of supposedly damaged natural resources of obvious value to man would be more profitable? Is immediate practical value of research results being claimed improperly in an effort to justify fundamental limnological studies for which no such justification should be necessary? These are questions which all biologists interested in water pollution should perhaps ask themselves. Many of these questions have no categorical answer, but it is hoped that the following discussion will prove thought-provoking. It may not only call attention to certain inconsistencies in claims made and terminology used, but may also indicate the need for revision of objectives or a change of emphasis in pertinent future investigations.

Biological investigation now is an integral part of water pollution detection and control, and biologists have become increasingly aware of their opportunities for contributing to progress in this field of work. Their ideas have been solicited and have been well received by other specialists. In trying to aid the advancement of their science, biologists owe it to their profession

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to seek thorough understanding of the practical problems of water pollution control. Understanding the complexity of these problems will make apparent the need for thorough and critical testing of new ideas previous to their widespread practical application.

First, it is necessary to consider the meaning of the term "pollution". The introduction of any foreign substance which merely alters the natural quality of water without materially interfering with any likely use of the water cannot be said in a practical sense to constitute pollution. Virtually every stream and lake in any inhabited region receives at least a trace of something which measurably or not measurably alters the natural quality of the water. What is significant or important from a practical standpoint is not the mere presence of the added material, but its influence upon the economic and esthetic value of the water, or on human welfare in a broad sense. It appears that most authorities in the field of water pollution control and abatement agree in defining water pollution as an impairment of the suitability of water for any beneficial human use, actual or potential, by any foreign material added thereto.

This definition agrees with repeatedly expressed judicial opinion, that is, with definitions of "pollution" and of "clean water" established by courts of law. The following legal definition, cited on page 100 of "Water Quality Criteria", a publication of the California State Water Pollution Control Board (4) is typical: "For the purposes of this case, the word 'pollution' means an impairment, with attendant injury, to the use of water that plaintiffs are entitled to make. Unless the introduction of extraneous matter so unfavorably affects such use, the condition created is short of pollution. In reality, the thing forbidden is the injury. The quantity introduced is immaterial." Other definitions cited agree essentially with this one.

In accordance with the above definition of the word pollution, a demonstrable change of some components of the biota of a stream clearly caused by the discharge of some waste into the water is not invariably evidence of pollution, any more than is a demonstrable chemical change. If it cannot be reasonably asserted that a hazard to human health or interference with some beneficial use of the stream such as fishing, must accompany a particular alteration of the biota, the change cannot correctly be said to indicate pollution. Even the discharge of a waste which eliminates virtually all organisms initially present in a very small or temporary stream capable of supporting no aquatic life of any value to man is not necessarily pollution. Oxygen-depleting organic wastes may be thoroughly mineralized in such streams through natural self-purification processes, so that only harmless substances and beneficial plant nutrients may reach larger watercourses to which these streams are tributary.

In agreement with the definition offered above, Beck (1) has defined pollution broadly as "the alteration of any body of water, by man, to such a degree that said body of water loses any of its value as a natural resource."

Patrick (28), on the other hand, has proposed a distinctly different, strictly biological definition. This author defines pollution as "any thing which brings about a reduction in the diversity of aquatic life and eventually destroys the balance of life in a stream." By way of explanation, it is further stated that "As conservationists interested in using rivers today - but not abusing them so that they are damaged in the future - this is the basis on which pollution should be judged. For it is by preserving the biodynamic cycle that the ability of a river to rejuvenate itself is maintained."

Unfortunately it is not clear just what is to be regarded as pollution according to the definition given by Patrick. Is any reduction in the diversity of aquatic life evidence of pollution which will eventually destroy the "balance of life", or only such a severe reduction of the diversity of life that the ability of the stream to "rejuvenate itself" is indeed destroyed? A reduction of species numbers is not always necessarily followed by the eventual destruction of the "balance of life" in a stream and of the ability of the stream to "rejuvenate itself" (i.e., to undergo natural self-purification). Patrick (28) has pointed out that the so-called "food chain" in aquatic environments "consists of many series of interlocking links so that if one series is broken another can take over so that the chain is not destroyed." It is well known, also, that in certain "zones" of streams heavily and continually enriched with organic wastes relatively few animal and plant species are present, as a rule, yet natural purification proceeds at a very rapid rate. Here, as in an efficient trickling filter, an ideally adapted and obviously vigorous, healthy, and in certain respects very well balanced biota of limited variety can exist, and the organic waste is mineralized far more rapidly and efficiently than it could possibly be in a previously uncontaminated stream with its original, primitive biota. The ability of the stream to "rejuvenate itself" certainly cannot be said to have been destroyed, or even impaired.

Thus, a stream can be seriously polluted, in any usual sense of the word, without lasting destruction of the "balance of life" and of self-purification capacity (which balance hardly can be permanent anyway, in any unstable environment). On the other hand, mere reduction of the diversity of aquatic life without impairment of any important "food chain" (i.e., the food supply of valuable fishes, etc.), or interference with existing stream uses, does not necessarily have anything to do with the conservation of natural resources. It appears, therefore, that the last-mentioned definition of pollution is unsatisfactory, from a practical standpoint, no matter how it was meant to be interpreted.

Careful consideration of the other pertinent writings of Patrick and of the proposed method of judging stream conditions leads to the conclusion that probably this author regards any marked reduction of the diversity of aquatic life as evidence of pollution.

Beck (1) states that "Patrick's methods suggest that the bio-dynamic cycle should be maintained in the primitive condition," allowing for no equitable stream use, for "any deviation from the primitive bio-dynamic cycle is interpreted by Patrick as evidence of pollution." Actually Patrick has not suggested that an entirely primitive condition of every stream biota should be maintained and has classified as "healthy" certain stream sections which evidently were not in the primitive state. A diversity of organisms approaching that found under undisturbed or primitive conditions does seem to have been regarded, however, as being characteristic of all "healthy", unpolluted waters. This interpretation of Patrick's views may be right or wrong. In any case, the need for clarification thereof, and for better agreement among biologists as to the meaning of terms too often loosely used, is apparent. It is noteworthy that Patrick's definition of pollution, quoted above, implies that an alteration of water quality cannot be pollution if it has no appreciable effect on the diversity of aquatic life, and it can be interpreted as meaning that a marked reduction of the diversity of aquatic life is always associated with pollutional abuse of the aquatic environment. Probably few if any workers directly concerned with water pollution abatement or control can approve such a definition.

One can hardly maintain that the relative worth of any biological environment depends on the number of species that it supports, rather than on the relative abundance of species of some importance or value to man. The presence of many different weeds does not usually contribute to the value of a pasture. Also, it is not always correct to assume that any marked modification of a natural environment and of its original, primitive biota will result in their economic degradation, that is, a reduction in value. The clearing, irrigation, and cultivation of desert and other almost worthless lands, the application of agricultural and other poisons for the control of various pests and weeds, and many other human activities can, indeed, greatly enhance the value of the affected lands while drastically modifying their biotas and reducing the numbers of species present. Not only the production of valuable crops is thus promoted, but sometimes also the production of equally valuable wild game. On the other hand, the destruction of only one or a few animal or plant species of outstanding value (e.g., by some selective poison) obviously can mean great loss. This loss is in no way ameliorated by the fact that most of the organisms in the same environment are not noticeably affected. It is evident that a change of any biota considered as a whole (e.g., the number of species represented, etc.) may not be a direct nor always reliable index and measure of damage to any valuable natural resource. There seems to be no sound basis for a general assumption of their strict or even approximate parallelism.

Although most authors evidently have recognized the economic significance of pollution, it appears that when devising their biological indices and measures of water pollution and its severity some biologists have completely disregarded all economic considerations. They seem to have curiously attached at least as much importance to the elimination of any species of diatom, protozoan, rotifer, or insect as to the disappearance of the most valuable food or game fish species. Yet, some have claimed that their measure of the harmful effects of pollution is a direct measure and therefore is more reliable than any chemical evidence or measure of pollution. Why the fate of harmless algal, protozoan or insect species can be said to indicate directly the extent of damage to a valuable fish population or to any commercial, recreational, or other use of water has not been explained.

If biological indices and measures of the severity of pollution cannot be relied upon always to reveal even the extent of damage to valuable aquatic life, they certainly do not indicate accurately the general pollutional status of any water. Water which is rendered biologically sterile by addition of some substances such as chlorine, or is appreciably enriched with some organic wastes, other than domestic sewage, may be of good sanitary quality and suitable for most ordinary domestic, agricultural, and industrial uses. On the other hand, water in which aquatic life is not markedly and adversely affected can be contaminated with dangerous pathogens or with chemicals which may seriously interfere with one or more of the above-mentioned uses. In view of the great variety of water uses, and the number and complexity of considerations (physical, chemical, biological, psychological, economic, and sociological) which evidently must enter into any reliable determination of the degree of interference with these uses by pollution, the evaluation of the over-all pollutional damage cannot be a simple matter. Any contention that some biological observations alone can cut across all of this complexity and show clearly whether the actual and potential uses of a stream have or have not been affected, and the magnitude of the total damage, would appear to be an oversimplification of the problem. It must be admitted that probably nobody has come forth yet with a clear statement of this claim. An yet, unless a different meaning is made perfectly clear, is not this claim implicit in every asseration to the effect that a generally applicable and reliable biological index or measure of the pollutional status or condition of streams has been devised and developed?

Biotic responses to all of the numerous and very different water pollutants are not alike. Early students of water pollution (23) (24) (31) dealt chiefly with pollution by putrescible organic wastes and particularly domestic sewage. In their day, the use of the term "biological indicators of pollution" when referring to organisms which respond in a certain way to heavy organic enrichment of their medium was perhaps justifiable. Untreated or inadequately treated domestic sewage then was by far the most important and perhaps the only well known and generally recognized water pollutant. Its discharge into public waters in amounts sufficient to bring about appreciable biotic changes being usually a hazard to human health, it was and is almost always pollution in any ordinary sense of the word. Today, the importance of pollutants other than domestic sewage is generally recognized. Yet, many authors still speak of "pollution indicators" when they actually are referring only to indicators of organic enrichment of water with putrescible organic wastes, which may or may not involve demonstrable damage to natural resources. Some readers are known to have been misled by this terminology, believing that the same biological indices are useful in detecting every kind of pollution.

Gaufin and Tarzwell (13), when reporting their studies of stream pollution with domestic sewage, obviously were considering the effects on aquatic life of an oxygen-depleting organic waste only. Nevertheless, such unqualified and seemingly general statements as their conclusion that "Pollutional associations are characterized by few species but large numbers of individuals" can be misleading. As the quoted authors well know, the numbers of many organisms initially present are reduced and the numbers of none are markedly increased in some waters polluted with toxic wastes, suspended solids such as silt, or even oxygen-depleting organic wastes discharged intermittently. These authors undoubtedly did not intend the conclusion in question to be a very broad generalization from their observational results having to do with one kind of pollution only. Their use of the expression "pollutional associations" for designating associations found in waters polluted with domestic sewage, or in waters enriched with putrescible organic matter, can be excused on the ground that no term that is more appropriate than the term "pollutional" has come into general use in the biological literature. Yet, this lack of a more precise terminology is not any less deplorable because the use of inappropriate terms, and terms which are not sufficiently specific, has become prevalent.

Beck (1) (2) explicitly confines his discussion to the subject of "organic pollution". He has proposed the use of a numerical "biotic index", which is said to be "indicative of the cleanliness (with regard to organic pollution) of a portion of a stream or lake" (2). He recognizes that his methods are "confined to fresh waters and encroaching salinity has a marked effect on the fauna of a stream." Inasmuch as many different pollutants, including toxic constituents of some organic wastes, likewise can have a marked effect on the fauna of a stream, it is apparent that Beck's methods may have only very limited applicability. It may be usable only in connection with the investigation and description of waters known in advance to contain no pollutants other than non-toxic putrescible organic matter.

Patrick (26) (27) (28), recognizing the importance of a variety of pollutants, apparently has attempted to devise a general procedure for the reliable biological detection and measurement of the different kinds of pollution. For reasons already indicated, however, this desirable objective appears to be attainable only when one defines pollution as "any thing which brings about a reduction in the diversity of aquatic life", which is not a generally acceptable definition.

Wurtz (38), while evidently realizing the existence and importance of a large variety of pollutants, seems to overlook completely the important differences of biotic responses to the different pollutants. Thus, his Figure 1 suggests that the same pollutional zones, including a "degradation zone" extending from the point of mixing of an effluent with the water of a stream to a "polluted zone" located some distance downstream, can be expected to occur in any heavily polluted stream, regardless of the nature of the pollutant (i.e., whether it be "organic", "toxic", or "physical"). Furthermore, he speaks of "pollution tolerant species" and of "non-tolerant organisms", suggesting that organisms are consistently tolerant or consistently non-tolerant with respect to all pollutants. Nowhere does he specify that he has in mind resistance to putrescible organic pollutants only, and there is considerable evidence that he has in mind all pollutants. In large degree, Wurtz seems to have adopted methods similar to Patrick's, but one of his innovations seems to require the probably impossible classification of all or nearly all aquatic organisms as "tolerant" and "non-tolerant" to all kinds of pollution, including the various toxicants, etc. Unfortunately, Wurtz does not include in his paper a list of all organisms considered by him to be tolerant and all those thought to be non-tolerant.

There can be no doubt that some of the so-called "pollution-tolerant" organisms, which actually are simply forms known to thrive in waters markedly enriched with organic wastes, are less tolerant with respect to some other water pollutants than a number of the species known as "clean-water" forms. For example, a species of Physa, a genus of snails generally believed to be resistant to organic pollution (1) has been found to be extremely susceptible to dissolved copper. Certain fish (e.g., centrarchids), may fly nymphs, etc., thought to be more susceptible than Physa to the effects of organic pollution, proved much more resistant to copper. An aquatic environment in which "clean-water" organisms are predominant might possibly be more seriously polluted than one with decidedly "pollutional" biota. The biological terminology evidently needs revision, so that the word pollution would not be used synonymously with organic enrichment.

It appears that, in general, very broad significance of the various biological indices of water quality and the severity of pollution has been only assumed and not actually demonstrated. This is well exemplified by the following quotations from the summary of one of Patrick's papers (27): "On the premise that the balanced physiological activities of aquatic life in surface waters are essential for the maintenance of healthy water conditions, it may be assumed that the most direct measure of this biodynamic cycle will indicate the condition of the water." It will be noted that we have here an assumption based upon a rather nebulous premise. Most writers have failed to supply entirely satisfactory, clear definitions of terms used (e.g., "pollution", "health", etc.) to show precisely what it is that they believe they can detect or measure biologically. Others have failed to use defined terms in a manner entirely consistent with their own definitions. The need for demonstration of the validity of some of the most fundamental assumptions concerning the reliability of pollution indices designed for general application has not been satisfied. Some authors seem to be of the opinion that the proof is unnecessary. It must be admitted that investigations designed to provide such proof would be extremely complex and difficult, and it is not likely that the search for this proof would be very rewarding, for there can hardly be a simple, general solution for the problem of pollution detection and measurement. Like a panacea, a general test for all kinds of pollutional damage is something for which biologists and engineers alike probably would be wise not to seek.

The value of fish as indicators of environment conditions and the importance of fish population studies in connection with the estimation of the intensity of water pollution now can be considered. Doubtless there is much more published information on the environmental requirements of fish than on the requirements of species of any other group of aquatic organisms excepting perhaps a few invertebrate species of outstanding economic importance. The vast quantity of published data relating to the water quality requirements of fish is partly revealed by a few recently prepared compilations and summaries of some of this information (4) (5) (8) (9) (10) (11) (17) (33). The resistance of many fish species to extreme temperatures, to unusual concentrations of dissolved oxygen and other dissolved gases, to variations of water salinity, and to extremes of pH, their susceptibility to the harmful effects of a great variety of toxic substances and of suspended solids of importance as water pollutants, the influence of some of these environmental factors upon embryonic development, growth, and activity, and so forth, have all been studied intensively. There exists also a voluminous literature on the food of fishes, their life history and reproductive requirements, their habitat preferences, movements, avoidance of adverse environmental conditions, and so on.

While it is evident that more is known of the environmental requirements of many fish than is known of the requirements of most, if not all, of the other aquatic organisms often considered as indicators of environmental conditions, the use of fish as indicators has received considerably less attention than has the use of other major groups, plant and animal, microscopic and macroscopic. Fisheries workers recognize the difficulty of adequately sampling fish populations even in bodies of water of moderate size, and this, along with the mobility of fishes, has been advanced as a reason for the unsuitability of fish as indicators of environmental conditions. But, other aquatic groups are difficult to sample too, as Needham and Usinger (25) have demonstrated in the case of the invertebrate macrofauna of a riffle. The difficulty of sampling and the mobility of fishes may not be the chief reasons why fish have not been given more consideration as indicators. The taxonomic groups which have received the most attention no doubt have reflected to some extent the special interests of investigators who happened to be working in the field of water pollution. Fish being the usual economic and recreational yield of stream productivity, their study has obvious applied value and so has required no additional justification. Further, the status of a fish population may indicate suitable or unsuitable environmental conditions, but when knowledge of this population is the end or aim of an investigation, the population status is not regarded as an index of anything else. The value of fish as indicators of the suitability of water for uses other than fishing has not been clearly demonstrated. Whatever the reasons may be, the emphasis in most discussions of the "biological indices" has been on groups other than fish, even though very little is known of the environmental requirements of the species of many of these groups.

The value of knowledge of fish populations in connection with the classification of aquatic environments has not been entirely overlooked. Ricker (32) made important use of the brook trout (Salvelinus fontinalis) and the Centrarchidae and Esocidae as a basis for his ecological classification of certain Ontario streams. Fisheries workers frequently use such expressions as "trout waters" or "bass waters", thus conveniently classifying waters according to the fish species for which the waters are well suited. European workers have made more formal use of such a system of stream classification (34) (37). Brinley and Katzin (3) have classified waters and named various pollutional "zones" of streams in the Ohio River drainage basin according to the kinds of fish populations found therein. As has been done with other animals and plants, some species of fish have been classified as to their "saprobic" preferences by a few authors (22) (24) (19) (35). The basis for such classification of fish is highly questionably. Patrick (26) (27) includes fish among the groups considered in her "biological measure" of stream conditions. Doudoroff (7) and Gaufin and Tarzwell (14) have emphasized the need for thorough fish population studies in connection with water pollution investigations and the determination of the pollutional status of waters.

Studies of fish populations in variously polluted waters, which reveal varying susceptibility of different fish species to pollutional conditions in their natural habitats, have been reported by a number of investigators (3) (6) (11) (20). However, sufficiently intensive sampling of fish populations has not often been undertaken in connection with routine pollution surveys and investigations, the sampling of other aquatic life having been probably more often emphasized when the scope of the biological studies has had to be limited. Inasmuch as it is not often possible adequately to study all of the aquatic biota, including the fish, the practical value of information to be obtained by concentrating attention on fish populations must be carefully weighed against that of information to be derived from equally intensive study of some of the other aquatic organisms, and from comparatively superficial study of the entire biota.

The absence or extreme scarcity of some fish in a stream below the point of entry of a waste, and not above the point of entry, strongly suggests that the waste is somehow detrimental to these fish; if valuable food and game fish species are among those believed to be adversely affected, pollution is indicated. Neither the presence nor the absence of fish is a reliable indication of suitability or unsuitability of water for domestic, agricultural, and industrial uses and for recreational uses other than fishing. Nevertheless, because of the great economic and recreational value of many fish species, this information is essential to sound classification of waters according to their pollutional status.

The presence of fish does not necessarily show that their environment has been suitable for them for a very long time, nor that the species found can survive indefinitely and complete their life cycles under the existing environmental conditions. However, the presence of thriving populations of non-migratory species, including numerous representatives of different age classes whose growth rates have not been subnormal, is significant. It suggests strongly that pollution which is highly detrimental to these fishes and to migratory species whose habitat preferences, natural food, and water quality requirements are quite similar has not occurred recently. For example, the presence of numerous cottids in Northwestern salmon and trout streams which receive organic wastes is believed to indicate that dissolved oxygen concentrations have been adequate for some time and other environmental conditions probably have been suitable not only for the cottids, but also for migratory salmon and trout. There is now no sound reason for believing that the presence of any invertebrate form is a more reliable and appropriate biological indicator of the suitability of past environmental conditions for the migratory salmonids than is the presence of cottids.

The value of waters used for fishing, and of the fisheries which they support, bears no fixed, direct relation to the number of fish species to be found therein, just as it bears no such relation to the number of species of other organisms present. Some 35 species of fish were collected in the Midwestern warm-water stream studied by Katz and Gaufin (20). Because of the scarcity of valuable food and game fishes, this small, polluted stream is not regarded as a valuable fishing stream. On the other hand, many cool, pure streams which are highly valued as trout and salmon streams contain very few fish species other than the salmonids. Indeed, the invasion of valuable trout waters by other fish species not initially present is generally regarded as evidence of degradation of these waters, for the numbers of trout usually decline when it occurs. Such a change of the fish population can be a result of increasing temperatures and probably also of enrichment (18). Warm, eutrophic waters can support a great variety of fish and other organisms, but trout waters which are approaching this condition can hardly be regarded as "healthy".

Some of the above statements seem to contradict Patrick's (26) (27) conclusion, based on a study of the Conestoga River Basin of Pennsylvania, that "The results of this study indicate that under healthy conditions a great many species representing the various taxonomic groups should be present." It is necessary, therefore, to examine the evidence on which the latter conclusion is based. It appears that, in accordance with Patrick's conception of what a "healthy" stream should be like biologically, only those stations where a variety of organisms judged to be fairly normal or typical was actually found were classed as "healthy". It is not surprising, therefore, that all of the stations classed as "healthy" had indeed this large variety of organisms. Chemical, bacteriological, and other data were collected and considered in selecting and classifying the stations studied. It is clearly indicated, however, that the variety of organisms found (which is the proposed index or measure of stream "health") also was a major consideration. Different conclusions perhaps would have been reached had the initial classification of the stations been based entirely on other criteria of obvious practical import (such as the abundance, condition, and growth rates of valuable native game fish, etc.) and had a greater variety of natural, unpolluted streams been examined. It is noteworthy also that certain stations which evidently were not much affected by waste discharges but lacked the usual variety of organisms (e.g., Station No. 152, in a stream section evidently suited for stocking with trout) were classed as "atypical" stations by reason of certain observed peculiarities, such as low water temperatures, unusual bottom or shore conditions, etc. Other stations which had the expected variety of organisms were classified as "healthy" stations despite noted peculiarities such as marked organic enrichment, unusually high BOD, high CO_2 content, high bacterial content, or great turbidity of the water. Thus, it appears that the rating of the stations was somewhat arbitrary.

When the possibility of certain pollutional damage specifically to fisheries is under consideration, it should be remembered that fishes have varying ecological requirements and habits, differ in their resistance to variations of water quality, and are not all dependent upon all aquatic organisms, nor upon the same organisms, for their food. It has been shown that the growth of some fish species is promoted in certain waters affected by the discharge of organic waste (21), whereas the same waters apparently are rendered unsuitable for some other species (20). A reduction of the number of species of fish-food organisms, with a great increase of abundance of some of the remaining species, which occur often in streams receiving various wastes, doubtless can be harmless or beneficial for some fish species, although this reduction may be detrimental to others. If they are not otherwise adversely affected by environmental changes, those fishes which can well utilize the abundant food organisms will thrive, while others may disappear. Whether the total effect on fisheries will be favorable or unfavorable clearly will depend on the relative commercial and recreational value of those fish populations which are favored and those which are affected adversely. An intensive study of the entire aquatic biota cannot always reveal the extent of pollutional damage to fisheries, unless the relative value of the various forms present (for man, or as food for important fishes) is considered.

To evaluate the effect of environmental changes on fisheries it is necessary to know what fish species were originally present, how highly each is valued, and in what way and to what degree each important species has been affected by waste discharges. The relative abundance and condition of individuals of different species in the waters under investigation and in suitable "control" areas, the growth-rates of different age classes, the palatability of the flesh, and possible interference with normal migratory movements or with other reproductive activities must all be considered. Fish collections taken by carefully planned netting will yield much of this information. Commercial and sport catch records, showing the take per unit of fishing effort, and various field observations (e.g., of spawning areas utilized, etc.) also can be very helpful. Inasmuch as the presence of wastes and other pollutants is by no means the only factor which can directly influence fish populations, the cause of observed differences of fish populations must be determined. In this connection, studies of the food of important fish species and of the relative abundance of available food organisms in waters which are affected and those which are not affected by waste discharges may be essential. However, if detection and evaluation of pollutional damage to fisheries is the only or primary objective of a biological investigation, an enumeration of the species of organisms of all taxonomic groups, or of some single invertebrate group, cannot be deemed a direct approach to the problem at hand. Judged only by its practical utility, it may be a waste of time, effort, and money, which perhaps could be far better expended on more directly pertinent studies. Indeed, it is difficult to imagine pollutional interference with any use or combination of uses of water which could usually be accurately and most efficiently evaluated in such an indirect manner.

A study of the influence of large amounts of organic waste on the ecology of the Tuolumne River of California has recently been completed by Warren (unpublished data). During August and September of 1952, the daily mean discharge rates of this river at the city of Modesto ranged from 293 to 822 cubic feet per second. The daily mean discharge rates of domestic and cannery waste introduced into the Tuolumne at Modesto ranged from 0 to 22.3 cubic feet per second. The 5-day biochemical oxygen demand of samples of this waste ranged from 60 to 575 parts per million. Dissolved oxygen concentrations at stations below the point of waste discharge ranged from zero to supersaturation during this time.

The objective of this study was to determine some of the effects of organic waste discharges on the ecology of the Tuolumne during the different seasons of the year. Some thirty miles of the river were studied, of which only the lower ten were influenced by waste discharges. The phytoplankton, zooplankton, benthic fauna, and fish were studied along with the physical, chemical, and bacteriological conditions in this river. The fishery phase of the investigation represented a small part of the total effort.

The investigation of the Tuolumne River now being complete and its objective more or less realized, it is interesting to consider how well other objectives might have been satisfied by this same study, planned and conducted as it was. For instance, had the objective been to determine the influence of the organic waste specifically on the fisheries of the Tuolumne, could not much of the effort devoted to the bacteriological, phytoplankton, zooplankton, and benthic faunal investigations have been far better expended on a thorough study of the fisheries? One is forced to conclude that were the objective to determine the status of the fisheries, the fish should have received most of the attention. This does not mean that studies of the plankton and of the benthic fauna are not necessary phases of an investigation so oriented. They may be quite necessary, but they should be so planned that the time and effort devoted thereto would not be out of proportion to their contribution to thorough understanding of the status or condition of the valuable fish populations.

The benthic fauna present at stations on the Tuolumne River below the point of waste discharge had many of the recognized "pollutional" characteristics during late summer and early fall. By this time, many of the "clean-water" species present at these stations earlier in the summer, and persisting at stations above the waste outfall, had disappeared. A marked reduction in species numbers had taken place, and at least one species occurred in unusually great numbers. While the bottom fauna showed changes that in accordance with most biological index methods would be regarded as evidence of pollution, rather intensive seining during mid-September resulted in the collection of 10 species of fish at stations above the point of waste discharge and 12 species at stations within the first ten miles below this point. The variety of fish present had certainly not been greatly altered by the introduction of wastes, even though the bottom fauna had been markedly modified.

Collections of young bluegills (Lepomis macrochirus) made in September showed the O-year class to grow faster at stations below the point of waste introduction than at stations above this point. The size difference persisted in the 1-year class. The difference in the O-year - class growth rates could probably be attributed to the greater abundance of zooplankton at the downstream stations.

While the above data are interesting, they cannot be taken as evidence that pollution of the Tuolumne damaging to fisheries did not exist. Some evidence indicated interference with a portion of the upstream migration of adult chinook salmon (Oncorhynchus tshawytscha), though the downstream migrant young were presumably unaffected, being apparently absent from the Tuolumne by the time of critical summer river flows and waste discharges. Juvenile shad may perhaps have been affected also. Had the principal objective of the Tuolumne River investigation been an evaluation of damage to fisheries resources by pollution, the study could not have been deemed complete in the absence of conclusive evidence that interference with salmon migrations and other possible damage to valuable fish populations had or had not occurred. None of the proposed "biological measures" of pollution intensity could have revealed the degree of such interference or damage. In order to obtain the crucial evidence required, it would have been necessary to emphasize the fisheries phase of the investigation.

It is not the purpose of this paper to discourage limnological research pertinent to water pollution problems, nor is it intended to deny the value of all biological indicators of pollution. There can be no doubt that a drastic modification of any natural aquatic biota, attributable to a change of water quality, can have highly undesirable aspects or consequences. Such changes presumably are detrimental to human use and enjoyment of natural waters more often than they are not. Many a readily demonstrable effect of wastes upon aquatic life in a valuable stream is suggestive of probable existing or incipient pollution which deserves close attention and investigation. Even before valuable fish populations have been materially affected by some potentially harmful pollutant, an observed detrimental effect upon other organisms which are somewhat more susceptible than fish may give warning of possible future damage to fisheries by continued or additional waste discharges. The nature and the source of existing or incipient pollution also may be revealed by appropriate biological indices. Finally, inasmuch as some of the organisms considered to be indicators of pollution are organisms which can directly interfere with human use or enjoyment of waters (e.g., unsightly slime-forming organisms such as Sphaerotilus, odor-producing algae, etc.), their unusual abundance may not be disregarded in evaluating over-all damage caused by pollution.

CONCLUSIONS

It must be concluded that every change or peculiarity of the flora and fauna of a stream which has been referred to as an index or measure of pollution is in reality only an index of environmental disturbance or environmental anomaly. The disturbance or anomaly indicated may or may not be pollutional in the sense that stream uses are interfered with. Pollution (i.e., interference with stream uses) can be negligible when the effect on the aquatic biota as a whole is great, and it can be severe when most of the aquatic life is unaffected. Gross pollution often can be demonstrated without any biological investigation. When biological investigation may be necessary, pollutional damage to valuable aquatic organisms can probably best be determined by concentrating attention upon these particular organisms. Yet, since all aquatic life forms are more or less sensitive to changes of water quality, the fate of any of them theoretically can be instructive, revealing something about the nature and magnitude of these changes that may not be obvious nor easily determined otherwise.

A genuine contribution to water pollution science can be made whenever the presence or relative abundance of living organisms of any kind can be shown to be a reliable index of something tangible that one may need to know in order fully to ascertain and understand the pollutional status of an aquatic environment. When proposing and describing the use of such biological indices, one should state specifically what it is that each is believed to indicate, carefully avoiding such general, vague, or abstract terms as "pollution" and "stream health", which may be variously understood. Does it indicate, for example, continual presence of dissolved oxygen in certain concentrations believed to be adequate for sensitive fish species? Does it indicate organic enrichment likely to interfere in some way other than through oxygen depletion with certain specific uses of water? Or does it indicate that particular toxic substances have not recently been present in concentrations likely to be injurious to fish, to man, or to certain crops? No simple biological indicator and no one measure of stream conditions can indicate all of these things. But any species can become a biological indicator of environmental conditions of possible interest as soon as its nutritional and other environmental requirements, its relative resistance to various toxic substances, etc., become known. Widely distributed sessile or sedentary organisms should be the most useful indicators of past conditions. Unfortunately, the water quality requirements of most of the "indicator organisms" have never been thoroughly investigated, so that there is no real knowledge of specific factors which limit their distribution and abundance. Probably nobody now knows just why any of the so-called clean-water organisms begin to disappear from waters subject to progressively increasing organic enrichment. Here is a field for future research which is far more promising than is, for example, the questionable classification of all aquatic organisms as "pollutional", "clean-water", or "facultative". If there are common sedentary organisms whose water quality requirements can be shown to correspond closely with those of valuable fish species, they are potentially useful indicators. At the present time, however, excepting instances of gross pollution, only fish themselves can be said to indicate reliably environmental conditions generally suitable or unsuitable for their existence.

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BIOACCUMULATION OF RADIOISOTOPES THROUGH AQUATIC FOOD CHAINS*

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INTRODUCTION

With an increasing number of atomic energy installations and their associated problems of disposal of liquid wastes, we recognize that more and more aquatic environments are going to be exposed to at least low concentrations of radioactive materials. For the safety of human populations who may be drinking water which contains such radioactive materials, a set of maximum permissible concentrations has been recommended (International Commission on Radiological Protection, 1955). By themselves, however, such recommendations are inadequate to define completely the radiological hazard which may develop through aquatic food chains. Where biological systems are involved, the organisms may accumulate certain isotopes to many times the initial concentrations in the water. There are many radioisotopes, however, that apparently are not biologically concentrated.

This paper describes some of the mechanisms involved in the accumulation of radioisotopes by aquatic organisms, with special reference to food webs and metabolic rates, and presents some examples of how the concentration of radioisotopes in organisms can be used to measure relationships between different species.

THE ACCUMULATION OF RADIOACTIVE MATERIALS

In order to interpret the reasons for, or to predict the concentration of, radioactive substances in aquatic forms, the biologist must appreciate that several basic processes are involved. The most important are: (1) the mode of uptake, which includes adsorption to exposed areas, absorption into tissues, and assimilation of ingested material; (2) retention, which is a function of the biochemistry of the particular elements and components involved, the site of deposition, the turnover rate, and the radioactive half-life; and (3) the mode of elimination, which may involve ion exchange, diffusion, excretion, and defecation.

MODE OF UPTAKE

The metabolism of the different radioelements and the relative importance of the different modes of uptake will fluctuate widely between different species, environments, and seasons. While this paper is principally concerned with assimilation through food chains, the processes of adsorption and absorption of radioactive substances directly from the water cannot be neglected. They are primary mechanisms by which inorganic materials are acquired by aquatic plants which are the food sources of the animals. The absorption of radioisotopes of strontium, barium-lanthanum and sodium by fresh-water fish has been demonstrated by Prosser et al. (1945). Absorption of radio-calcium has been demonstrated by Lovelace and Podoliak (1952) and by Rosenthal (1956). Chipman (1956) showed that cesium readily passed through excised pieces of tuna skin but that there was little absorption of strontium or ruthenium from sea water. Fish immersed in effluent from the Hanford reactors concentrated Na^{24} in the tissues about 130-fold. Direct absorption of other isotopes which are dominant in the effluent, including Cr^{51}, Cu^{64}, P^{32}, As^{76}, and rare earths, appeared to be inconsequential, however. In fish that live downriver from the Hanford reactors, sorption of radioactive materials directly from the effluents accounts for only about 1.5 percent of the total radioactivity. Consequently, sorption is of much less importance than ingestion in the uptake of radioactive materials by Columbia River fish.

Adsorption occurs almost instantaneously, as has been demonstrated with yttrium on cells of the marine alga Carteria by Rice (1956), while equilibrium by absorption is usually reached by algal cells (Whittaker, 1953) and by vascular aquatic plants (Hayes, et al., 1952) within a few hours. Because of the rapid uptake of radioisotopes by these mechanisms, Columbia River plankton, composed almost entirely of diatoms, appears to reach equilibrium about one hour after floating into the zone containing effluent from the Hanford reactors (Foster and Davis, 1955).

Assimilation of ingested materials is the dominant means by which many radioactive materials become accumulated in animals since the bulk of their essential elements is obtained from their food. The contribution of food webs to the concentration of radioisotopes in aquatic animals was apparent from samples collected from the Columbia River soon after the first Hanford reactors began operation. Fish collected downriver from the reactors were approximately 100 times as radioactive as laboratory fish that were exposed to equivalent mixtures of the effluent, but fed uncontaminated food. Bottom animals, particularly herbivorous insect larvae, were found to be even more radioactive than the fish. The concentrations of radioactive materials in Columbia River organisms have never approached hazardous levels, however.

DIFFERENCES BETWEEN SPECIES

The relative concentrations of beta emitters in various Columbia River organisms are shown in Figure 1. There are several reasons for the differences

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which occur between these species.

(1) Several radioisotopes are involved and their relative proportions are different in the various organisms. A good indication of the proportions of the several isotopes can be obtained from curves like those in Figure 2 which show the characteristics of the radioactive decay of the isotope mixtures peculiar to each species. The positions of the curves in Figure 2 at zero time approximate the relative concentrations of radioisotopes in the water, small fish [Richardsonius balteatus (Richardson)], caddis larvae [Hydropsyche cockerelli, Banks], and plankton of the Columbia River during late summer months. The predominance of short-lived isotopes in the water is shown by the steep slope of the bottom curve. Short-lived emitters also contribute most of the radioactivity in the plankton but these have virtually disappeared by the fifth day. The remaining activity in the plankton, which is only about 20 percent of that originally present, emanates from P^{32} and other isotopes with half-lives greater than two weeks. In the caddis larvae and fish, only about 5 percent of the initial radioactivity originates from short-lived emitters. After the first day the rate of decay is quite uniform and characteristic of P^{32} (half-life 14.3 days). The dominance of the P^{32} has been confirmed by radiochemical analysis.

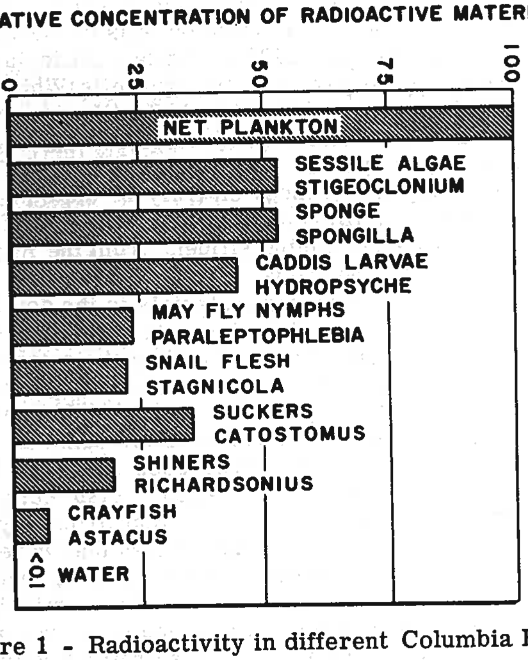

Figure 1 - Radioactivity in different Columbia River organisms.

The relative proportions of the several isotopes differ from one organism to another not only because of dissimilarities in the chemical composition and physiological demands of the different forms but also because of the different sorption characteristics which vary with morphology. Food chains are also important since they tend to "select for" isotopes of the essential elements, in this case P^{32}, and to "select against" nonessential elements. During the late summer months, the concentration of P^{32} in small fish of the Columbia River may be 165,000 time that of the water. On the other hand, As^{76} is barely detectable in the fish although it is responsible for a substantial fraction of the radioactivity in the water.

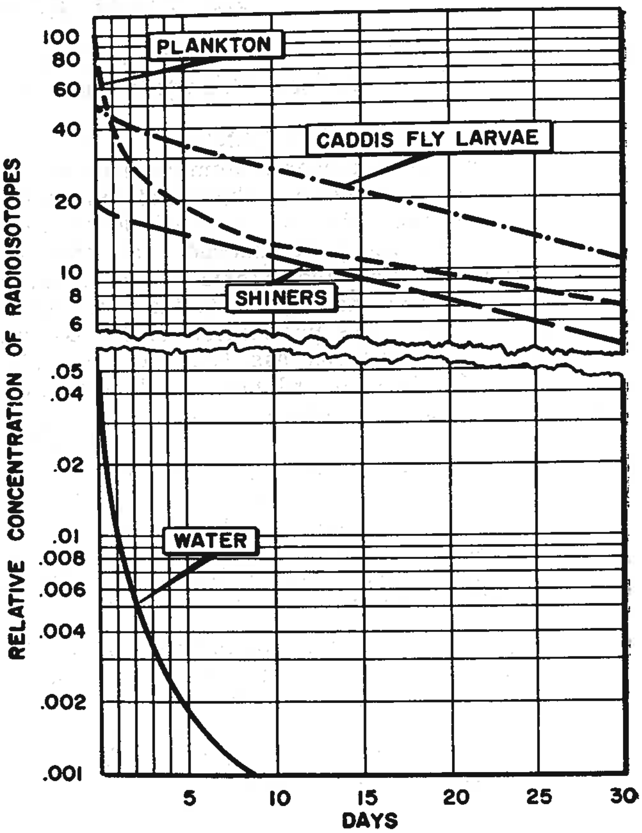

Figure 2 - Radioactive decay in different organisms and Columbia River water.

The marked variation in the relative abundance of different isotopes which can occur at different trophic levels and even between similar species has recently been pointed out by Krumholz (1956). From data collected at White Oak Lake, which received a variety of radioactive wastes from the Oak Ridge National Laboratory, Krumholz states: "Although radiophosphorus was generally accumulated in much greater amounts than any other radioelement by the organisms that served as food for the fish, that element made up only a small portion of the total radiomaterials concentrated in the fish tissues; whereas radiostrontium, which was present in the food organisms in only relatively small quantities, was accumulated in high concentrations in the fish skeletons. Furthermore, although the contents of the bluegill stomachs contained more radioactivity, on the average, than those of the black crappies, the crappies accumulated considerably greater amounts of radiomaterials in the hard tissues than the bluegills did. The bluegills, on the other hand, accumulated more radiomaterials in the soft tissues than the black crappies. Both species concentrated radiostrontium in quantities 20,000 to 30,000 times as great as those in the water in which they lived."

(2) Variation in moisture content between different organisms is a second reason for the differences in concentration of radioisotopes shown in Figure 1. Chemical composition is also a factor since we are

actually concerned with the quantity of a particular element in a unit mass of live tissue. The percentage of the live weight of the Columbia River plankton, caddis larvae, and minnows which is contributed by the inorganic ash is respectively 16, 2.2, and 3.0; and the concentration of phosphorus in the living organisms is about 150 ppm for plankton, 2,000 ppm for caddis larvae, and 6,000 ppm for minnows. Even greater differences may occur between the different tissues of an individual. Figure 3 shows how the concentration of radioactive materials varies between different tissues of whitefish in the Columbia River. Since virtually all of the activity is from P^{32} this gives a good indication of the relative concentration of phosphate in the different tissues.

(3) A third reason for differences in concentrations of radioisotopes between different organisms is their relative position on the food pyramid. Although elements are exchanged continuously between the water and the organisms of a food web, there is a mean retention time for each element in each organism. Each trophic level thus serves as a kind of pool or reservoir in which essential elements are retained for some mean length of time before they are passed on to the next level. The size of each pool will be governed by the total amount of an element held by the entire biotic mass making up the particular trophic level. A major fraction of most radioactive contaminants accumulated by aquatic life will be held by the plankton and benthic algae because of their relatively large total mass. Rigler (1956) found that over 95 percent of the P^{32} added to a lake was taken up by plankton (including bacteria) within 20 minutes. But retention time is not necessarily a function of the size of the pool. Indeed it is more apt to be inversely related since most elements will remain for a longer time in the larger organisms than in the small plant forms, although the small plants constitute the largest pool. Since, in the Columbia River, we are dealing with a flowing stream where isotopes are added at a more or less constant rate, much of the mineral exchange system can be considered as a once-through process rather than a cycle. Some radioactive decay will occur while the isotopes are retained in each trophic level. This decay, and thus the effective retention period, should be measurable by a progressive decline in specific activity -- the concentration of an isotope per unit mass of the element. For example, under certain conditions midge larvae in the Columbia River may contain on the order of 4 μc P^{32}/g of P and the small fish which eat the midge larvae about 0.5 μc P^{32}/g of P . Since the half-life of P^{32} is two weeks, the phophorus deposited in the fish must be, on the average, about six weeks "older" than that in the midge larvae. The reltive "age" of the isotope will differ between species and differ between species and will change with the age, sixe, and growth rate of the individual and with the seasons. The decrease in specific activity will, of course, be more apparent for short-lived isotopes than for those with half-lives of several weeks or more.

The specific activity of the river biota should be appreciably lower than that of the water not merely because of the time required to incorporate the isotope into the organisms but also because of the "pools" of elements fixed in the biota and sediments. When a radioisotope is first introduced into a body of water it

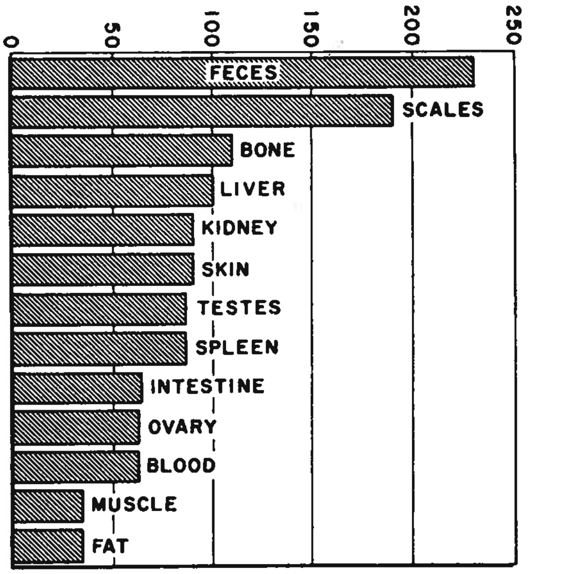

Figure 3 - Radioactivity in different tissues of Columbia River fish.

will be isotopically diluted with the stable form of the element which is dissolved in the water. Soon, it also will become isotopically diluted by exchange with the stable form of the element which has not been in solution. With a single addition of isotope into a "static" environment, the specific activity will eventually become uniform throughout the biota. Reservoirs of phosphates in the solids of lakes have been described by Hutchinson and Bowen (1950) and Hayes and coworkers (1952), who have studied phosphorus exchange with the use of P^{32} .

RATE OF ACCUMULATION BY AQUATIC ORGANISMS

The nearly instantaneous uptake of isotopes by adsorption and the rapid uptake by absorption have been mentioned. When animals are chronically feeding on radioactive materials, the rate at which their concentration of the isotopes approaches equilibrium will be a function of the radioactive and biological half-lives of the particular isotope involved.

Figure 4 shows the rate at which caddis fly larvae (Hydropsyche cockerelli) accumulated radioactive materials (mostly P^{32}) when fed filamentous algae (mostly Spirogyra) that had been cultured in reactor effluent. If there was no biological turnover of phosphorus in the caddis larvae, the time required to reach some fraction of the equilibrium level would be a function of the radioactive decay constant and could be predicted from the equation:

$$\frac{Q_t}{Q_e} = 1 - e^{-\lambda t}$$

where Q_e is the amount of the isotope present at equilibrium, Q_t is the amount present at some time (t) before equilibrium is reached, and λ is the radioactive decay constant.

Since true equilibrium will only be reached after infinite time, we can consider practical equilibrium to occur when $Q_t = 0.9\, Q_e$, and solve the equation for t. For any isotope, t will be equal to the half-life multiplied by $\frac{-\ln 0.1}{.693}$. For P^{32} it is approximately 47 days.

The curve presented in Figure 4 shows a much shorter time which indicates that significant biological turnover is present. The equation is easily modified to take this into account:

$$\frac{Q_t}{Q_e} = 1 - e^{-\delta t}$$

where δ is the sum of λ and β, where β is the constant for biological half-life. A 0.9 of equilibrium,

$$t = \frac{-\ln 0.1}{\beta + \lambda}$$

From Figure 4, t is about 50 hours and

$$50 = \frac{2.302}{\frac{.693}{T_b} + \frac{.693}{343}}$$

(343 is the half-life of P^{32} in hours).

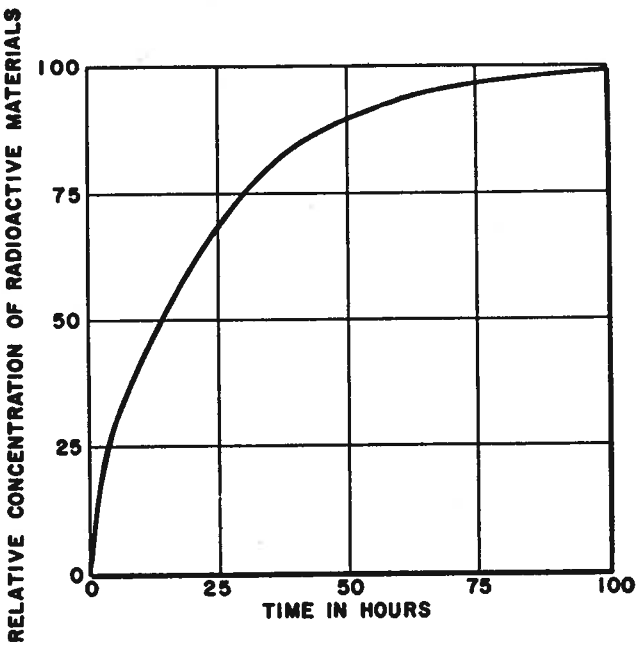

Figure 4 - Rate of accumulation of effluent isotopes by caddis fly larvae.

The biological half-life, T_b , is about 16 hours. Under such conditions the specific activity of the P^{32} will not diminish appreciably at this trophic level.

If laboratory tests can be carried out in conjunction with field observations, some interesting ecological relationships can be deduced. For example, we might measure the concentration of P^{32} in small minnows collected from a contaminated environment and find this to be $2 \times 10^{-3}\,\mu c/\text{gram}$. If the average size of the minnows was 5 grams, then each fish would have a body burden of about $10^{-2}\,\mu c$ of P^{32}. From a laboratory test, which duplicated field conditions as closely as possible, we might find that 0.9 of Q_e was reached in 20 days. Then

$$\delta = \frac{-\ln 0.1}{t} = \frac{2.302}{20} = 0.115$$

The same test might show that half of the ingested P^{32} was assimilated and deposited ($a = 0.5$). Assuming the concentration of P^{32} in the river fish to be in equilibrium with the environment and neglecting growth.

$$Q_e = \frac{aq}{\delta}$$

where q is the quantity of P^{32} ingested per unit time -- in this case each day. Then,

$$10^{-2}\,\mu c = \frac{0.5\, q}{0.115}$$

$$q = 2.3 \times 10^{-3}\,\mu c/\text{day}.$$

and

In order to have reached the observed concentration of P^{32}, each minnow must have consumed about $2.3 \times 10^{-3}\,\mu c$ of P^{32} each day. If, from stomach analyses, we have found that the fish feed predominantly on midge larvae and from field collections we have found that the midge larvae have a concentration of P^{32} of about $10^{-2}\,\mu c/g$, then we can surmise that each minnow has been eating about 0.23 grams of the midge larvae each day.

SEASONAL VARIATIONS

Since most aquatic animals are poikilothermic, their metabolic rates, and thus their feeding rates, change with variations in temperature and so with the seasons. For those aquatic forms that accumulate radioactive substances principally via ingestion, the concentration of radioisotopes fluctuates with metabolic rate. Figure 5 shows the seasonal fluctuations which occur in the radioactivity of plankton (diatoms) and minnows (Richardsonius balteatus) in the Columbia River. Fluctuations in plankton are quite similar to those in the water since the radioisotopes are acquired by direct absorption and adsorption (Foster and Davis, 1955). On the other hand, fluctuation in the radioactivity of the minnows is more closely related to the temperature. The 75-fold increase in concentration of radioisotopes in the fish between winter and late summer does not mean simply that the fish are eating 75 times as much food. The seasonal fluctuations result from the interaction of all of the factors mentioned above which influence the accumulation of radioactive materials. As the feeding rate increases for each organism, its intake of radioisotopes may be disproportionately large. The consumer is not only eating more grams of food, but each food organism has become more radioactive, and the effective time intervals between trophic levels have become less. Possibly the food habits of the species in question have also changed. A complete evaluation of the seasonal fluctuations in any one species would require an immense amount of work, not only on the food habits of the species but also on its physiology and on the radioactive contamination of its food organisms.

Not all seasonal variations are associated merely with temperature since deviations may occur where complex life cycles are involved. This occurs in immature insects which are less radioactive during quiescent periods than when the larvae or nymphs are feeding. It is also true of salmon that return to the Columbia River to spawn. The adult salmon virtually stop feeding when they enter fresh water, and consequently pick up very little radioactive material. Krumholz (1956) also observed definite seasonal changes in the accumulation of radiomaterials by fish of White Oak Lake. These corresponded to some extent with seasonal changes in temperature. He noted, however, that the accumulation of radioisotopes in black crappie and bluegills stopped at the first of August when the temperature reached about 80° F. He attributes the rapid loss of radioactive materials during August and September to a period of summer dormancy for these species.

SUMMARY

Some radioactive materials introduced into aquatic environments may be accumulated by the organisms. The amount of accumulation will vary over many orders of magnitude depending upon the kinds of isotopes involved and many physical, chemical, and biological factors. Such concentration is of considerable importance in the control of radiological hazards and the aquatic biologist has definite responsibilities in this area.

The processes of adsorption and absorption are of major importance in the uptake of radioisotopes by plants but appear to be of less importance than the food chain in the uptake by aquatic animals. The concentration of radioactive substances will vary between species and tissues and will fluctuate according to food habits, life cycles, and seasonal changes.

Within the biotic mass, a major fraction of most radioactive contaminants will be held by the organisms which make up the primary trophic levels. In a flowing stream, the specific activity of a radioisotope will diminish along the food chain. Where the turnover rates of certain isotopes can be measured, inferences can be drawn on feeding habits.

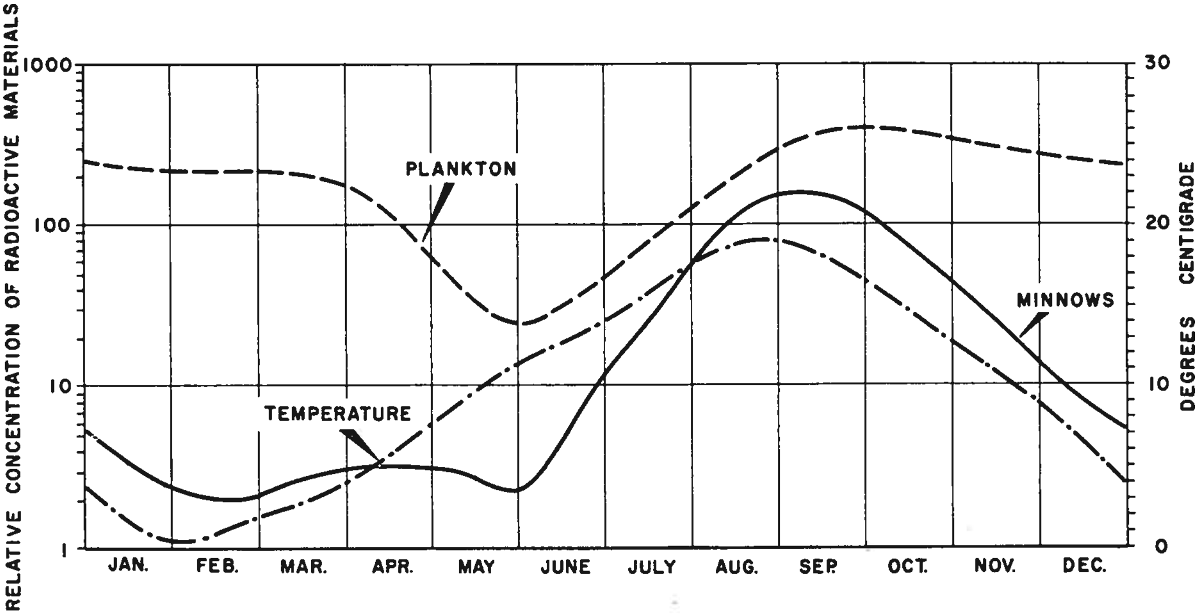

Figure 5 - Seasonal fluctuations in radioactivity of Columbia River organisms.

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